Federal Lands Greenhouse Gas Emissions and Sequestration in the United States: Estimates for 2005–14

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U.S. Department of the Interior
U.S. Geological Survey

Cover. South Pass; Oregon, Mormon Pioneer, California, and Pony Express National Historic Trails Corridor; Wyoming. Photograph by Bob Wick, Bureau of Land Management, September 16, 2010.

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U.S. Geological Survey
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The project’s initial stages benefited greatly from the work of Robin O’Malley of the USGS, who organized numerous interagency meetings that lead to valuable data exchange and expertise assistance.

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Conversion Factors

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	10.76	square foot (ft^2)
hectare (ha)	2.471	acre
	Volume	
barrel (bbl; petroleum, 1 barrel=42 gallons)	0.1590	cubic meter (m^3)
	Mass	
kilogram (kg)	2.205	pound avoirdupois (lb)
metric ton (t)	1.102	ton, short (2,000 lb)
metric ton (t)	0.9842	ton, long (2,240 lb)
	Carbon density	
kilogram per square meter (kg/m^2)	0.2048	pound per square foot (lb/ft^2)

Abbreviations

BLM	Bureau of Land Management
CH_4	methane
CO_2	carbon dioxide
CONUS	conterminous United States
DOM	dead organic matter
DOS-TEM	Dynamic Organic Soil version of the Terrestrial Ecosystem Model
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
GPP	gross primary productivity
IBIS	Integrated Biosphere Simulator
km	kilometer
LUCAS	Land Use and Carbon Scenario Simulator
LULC	land use and land cover
m	meter
t CO_2 Eq./ha	metric tons of carbon dioxide equivalent per hectare
t CO_2 Eq./ha/yr	metric tons of carbon dioxide equivalent per hectare per year
MMT CO_2 Eq.	million metric tons of carbon dioxide equivalent
MMT CO_2 Eq./yr	million metric tons of carbon dioxide equivalent per year
MSHA	Mine Safety and Health Administration
N_2O	nitrous oxide
NBP	net biome productivity
NEP	net ecosystems productivity
NPP	net primary productivity
OCS	Outer Continental Shelf
ONRR	Office of Natural Resources Revenue
PADUS	Protected Areas Database of the United States
Ra	autotrophic respiration
Rh	heterotrophic respiration
TEC	total ecosystem carbon
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey

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Abstract

In January 2016, the Secretary of the U.S. Department of the Interior tasked the U.S. Geological Survey (USGS) with producing a publicly available and annually updated database of estimated greenhouse gas emissions associated with the extraction and use (predominantly some form of combustion) of fossil fuels from Federal lands. In response, the USGS has produced estimates of the greenhouse gas emissions resulting from the extraction and end-use combustion of fossil fuels produced on Federal lands in the United States, as well as estimates of ecosystem carbon emissions and sequestration on those lands. American Indian and Tribal lands were not included in this analysis. The emissions estimates span a 10-year period (2005–14) and are reported for 28 States and two offshore areas. Nationwide emissions from fossil fuels produced on Federal lands in 2014 were 1,279.0 million metric tons of carbon dioxide equivalent (MMT CO_2 Eq.) for carbon dioxide (CO_2), 47.6 MMT CO_2 Eq. for methane (CH_4), and 5.5 MMT CO_2 Eq. for nitrous oxide (N_2O). Compared to 2005, the 2014 totals represent decreases in emissions for all three greenhouse gases (decreases of 6.1 percent for CO_2, 10.5 percent for CH_4, and 20.3 percent for N_2O). Emissions from fossil fuels produced on Federal lands represent, on average, 23.7 percent of national emissions for CO_2, 7.3 percent for CH_4, and 1.5 percent for N_2O over the 10 years included in this estimate.

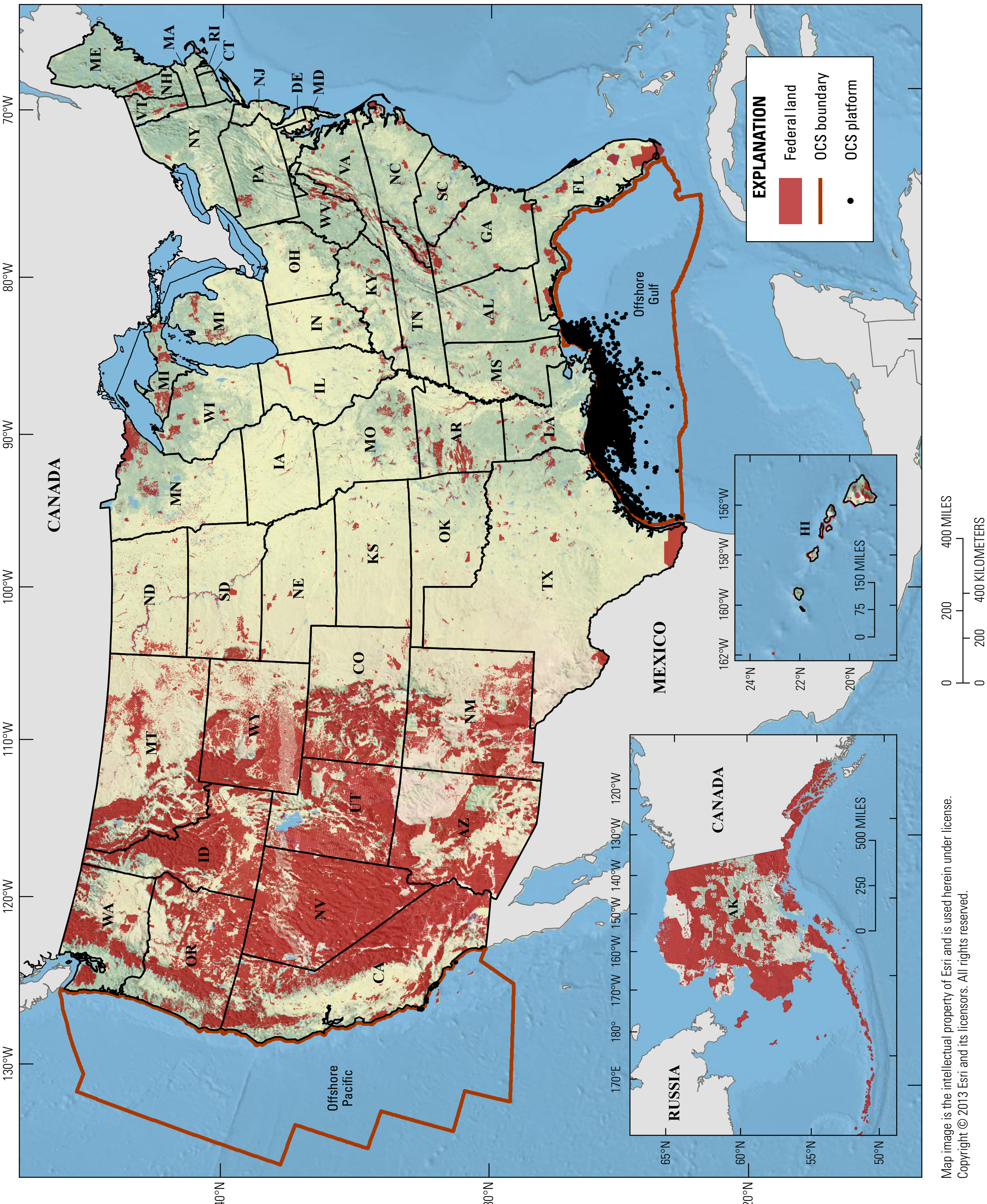
In 2005, Federal lands of the conterminous United States stored 82,289 MMT CO_2 Eq. in terrestrial ecosystems. By 2014, carbon storage, or sequestration, was estimated at 83,600 MMT CO_2 Eq., representing an increase of 1.6 percent, or 1,311 MMT CO_2 Eq. Soils stored most of the ecosystem carbon (63 percent), followed by live vegetation (26 percent) and dead organic matter (11 percent). The rate of net carbon uptake in ecosystems ranged from a sink (sequestration) of 475 million metric tons of carbon dioxide equivalent per year (MMT CO_2 Eq./yr) to a source (emission) of 51 MMT CO_2 Eq./yr because of annual variability in climate and weather, rates of land-use and land-cover change, and wildfire frequency, among other factors. At the national level, the USGS estimates that terrestrial ecosystems (forests, grasslands, and shrublands) on Federal lands sequestered an average of 195 MMT CO_2 Eq./yr between 2005 and 2014, offsetting approximately 15 percent of the CO_2 emissions resulting from the extraction of fossil fuels on Federal lands and their end-use combustion.

The USGS estimates presented in this report represent a first-of-its-kind accounting for the emissions resulting from fossil fuel extraction on Federal lands and the end-use combustion of those fuels, as well as for the sequestration of carbon in terrestrial ecosystems on Federal lands. The net CO_2 emissions estimate, which is the difference between the emitted and sequestered CO_2, provides an informative combined result describing the emissions (fossil fuel extraction and end-use combustion) associated with a State's Federal lands and sequestration on those same lands. The estimates included in this report can provide context for future energy decisions, as well as a basis to track change in the future.

Introduction

In January 2016, the Secretary of the U.S. Department of the Interior tasked the U.S. Geological Survey (USGS) with producing a publicly available and annually updated database of estimated greenhouse gas emissions associated with the extraction and use (predominantly some form of combustion) of fossil fuels from Federal lands (fig. 1). In response, the USGS began a study of greenhouse gas emissions and carbon sequestration on Federal lands in the United States; the study produced the requested estimates for 2005–14. National estimates of greenhouse gas emissions are published by the U.S. Environmental Protection Agency (EPA), but these estimates do not report emissions from Federal lands specifically. Therefore, this USGS effort relies heavily on the established methods used by the EPA but uses State-level data specific to emissions associated with Federal lands.

Fossil fuel extraction and combustion emit greenhouse gases. Industrial injection of greenhouse gases into the subsurface for enhanced hydrocarbon production or for greenhouse gas storage are forms of sequestration. Industrial sequestration is not included in the estimate because of the small magnitude


EXPLANATION
Federal land
OCS boundary
OCS platform
CANADA
MEXICO
RUSSIA
Offshore Gulf
Offshore Pacific
ME
NH
VT
MA
RI
CT
NY
NJ
DE
MD
PA
VA
WV
NC
SC
GA
FL
OH
KY
TN
AL
MS
MI
IN
IL
WI
MN
IA
MO
AR
LA
ND
SD
NE
KS
OK
TX
MT
WY
CO
NM
ID
UT
AZ
WA
OR
NV
CA
AK
HI
70°W
80°W
90°W
100°W
110°W
120°W
130°W
40°N
30°N
20°N
0 200 400 MILES
0 200 400 KILOMETERS
0 250 500 MILES
0 75 150 MILES
65°N
60°N
55°N
50°N
170°E
180°
170°W
160°W
150°W
140°W
130°W
120°W
24°N
22°N
20°N
162°W
160°W
158°W
156°W

of current industrial sequestration and a paucity of available data. Ecosystems can also sequester or emit greenhouse gases. Therefore, the estimated fossil fuel-associated emissions are supplemented with the estimated net flux of carbon associated with plants and other organisms (ecosystems) on Federal lands. The inclusion of ecosystem estimates provides the opportunity to calculate a net emission result (for carbon dioxide [CO_2] only) by comparing the fossil fuel-associated emissions estimates with those for carbon stored or released from ecosystems on Federal lands. For clarity and brevity, in this report, the term "emissions" generally, but not exclusively, refers to fossil fuel-associated emissions and the term "sequestration" commonly refers to sequestration in terrestrial ecosystems. However, both industrial fossil fuel activities and ecosystems emit and sequester greenhouse gases. For ease of comparison between fossil fuel-associated emissions and ecosystems flux estimates, the values in this report are presented in equivalent amounts of CO_2 gas.

The discussion of the estimates is separated into two sections: "Fossil Fuel-Associated Emissions of Greenhouse Gases from Federal Lands" and "Terrestrial Ecosystems-Associated Carbon Emissions and Sequestration on Federal Lands." The first covers emissions of CO_2, methane (CH_4), and nitrous oxide (N_2O) from the extraction and eventual end-use combustion of fossil fuels produced on Federal lands, and the second deals with the sequestration and emission of carbon in terrestrial ecosystems on Federal lands. Both sections detail the data sources, methodology, and results specific to the estimates. The report concludes with a discussion of the net emissions attributed to Federal lands; these are the estimates produced by summing the emissions and sequestration results. Appendixes 1 and 2 supply additional information regarding the data sources and methodology.

Figure 1 (facing page). Map showing the onshore Federal lands (excluding American Indian and Tribal lands) and offshore Federal Outer Continental Shelf (OCS) planning areas (offshore Pacific and offshore Gulf) included in the emissions and sequestration estimates. The Federal Atlantic and Alaska OCS planning areas were excluded because they did not have fossil fuel production during the study period. Federal lands were modified from the U.S. Geological Survey Protected Areas Database of the United States (U.S. Geological Survey, 2016). OCS boundaries and platforms are from Minerals Management Service (2006a, b), Bureau of Ocean Energy Management (2011), and Bureau of Safety and Environmental Enforcement (2014).

Fossil Fuel-Associated Emissions of Greenhouse Gases from Federal Lands

Introduction

For the emissions portion of this study, we estimated the greenhouse gas emissions (CO_2, CH_4, and N_2O) resulting from the extraction and end-use combustion of fossil fuels derived from U.S. Federal lands, including offshore areas. The Gulf of Mexico Outer Continental Shelf (OCS) and Pacific OCS planning areas are included in this report and referred to as offshore Gulf and offshore Pacific, respectively. No other OCS areas are included in this report because they did not produce fossil fuels during the period of this study. Emissions are produced through two processes: (1) the combustion of fuel for electricity generation, mechanical work, heating, or use as a feedstock and (2) the fugitive emission of gases during the processes of extracting and moving fuel. Fugitive emissions were attributed to the areas where the fuels originated; the location of the eventual combustion of the fuel, whether on Federal, State, private, or international territory, was not a factor. If the fuel was sourced on Federal lands, it was included in the estimate regardless of where it was used. All references to emissions in this section are associated with fossil fuels extracted from Federal lands in States and offshore areas. American Indian and Tribal lands were not included in this analysis.

Data Sources

Four main types of data support the emissions estimates in this report: (1) Federal lands fuel (oil, gas, and coal) production; (2) emissions from coal mines and oil and gas infrastructure (fugitive emissions); (3) national- and State-level energy-consumption and emissions data for apportioning extracted fuel to end-use fuel type and economic sector; and (4) process-specific emission factors that determine the volumes of greenhouse gases emitted by combusted fuels. A general discussion of the data sources is provided here, and an in-depth listing of data sources is provided in appendix 1.

Data on Federal lands fuel production are collected as part of royalty tracking by the Office of Natural Resources Revenue (ONRR) in the U.S. Department of the Interior. The ONRR is the Federal data source for revenue generated from fuel production on Federal lands. Production data collected by the ONRR (made available to the USGS via Memorandum of Agreement MOA16–5285) were the main input to the emission estimate calculations. These values include coal, oil, and natural gas production from Federal lands in 28 States and the Federal offshore Pacific and offshore Gulf. No fossil fuels were produced on Federal lands in the remaining 22 States or the Atlantic and Alaska offshore areas during the study period. In addition, the ONRR production data provided to the USGS

could not be attributed to specific Federal land management agencies. Data from the ONRR were available at the level of detail required for this project starting in 2005; data availability was through 2014, the final complete year when this project began.

Fugitive emissions include measured or estimated releases of CH_4 from underground and surface coal mines (both active and abandoned) and CO_2 and CH_4 emissions from oil and gas infrastructure such as wells, pipelines, compressors, and storage tanks. These data were provided by the EPA but collected by the Mine Safety and Health Administration (MSHA). The MSHA measures emissions from some underground coal mines, and mine operators submit other emissions estimates and measurements to the EPA's Greenhouse Gas Reporting Program.

The third set of values required to complete the emissions estimate consists of national- and State-level energy production, sector usage, refining, and export statistics. The source of these statistics is the U.S. Energy Information Administration (EIA), which is part of the U.S. Department of Energy. These published statistics (see references in appendix 1) were used to generate ratios for apportioning the Federal production volumes to end-use fuel types and economic sectors. This allocation was necessary because it is often impossible to track coal, oil, or gas from a specific Federal source as it moves through the fuel supply system to its eventual endpoint where emissions are generated. Fuels from most Federal lands are combined with fuels from private and State lands in pipelines, containers, or shipments, and once combined, the origins of the fuels are no longer traceable. In 2014, approximately 42 percent of the total crude oil produced in the United States was refined into motor gasoline (U.S. Energy Information Administration, 2015c). We assumed that this ratio also holds for crude oil from Federal lands, such that if a State produced 1 million barrels of oil from Federal lands, it would be assumed that 42 percent of the 1 million barrels was refined into motor gasoline. Though the actual number is certainly different, it is not possible with the currently available data to determine the amount of motor gasoline produced from a State's Federal-lands crude oil. Ratio-based scaling from national- or State-level production volumes was used throughout the estimate calculation for amounts of products refined from crude oil, industrial uses of natural gas, sector usage for coal combustion, and international fuel exports. The specific EIA sector usage, refining, and State export reports used in this calculation are listed in appendix 1.

Emission factors are the values used to convert volumes of fuel combusted into amounts of greenhouse gases emitted. These conversions differ by the input fuel and the sector of the economy where that fuel is consumed. The EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks (hereafter EPA Inventory; U.S. Environmental Protection Agency, 2016b), an annual publication of total U.S. greenhouse gas emissions, is the source of all emission factors used in this study. In addition, the EPA Inventory's calculation methodology is the basis for the methods used in this study.

Methodology

Introduction

The methods used in this study to estimate greenhouse gas emissions from fossil fuel produced on Federal lands are adapted from the more exhaustive methodology described in the EPA Inventory and its associated annexes (U.S. Environmental Protection Agency, 2016a, b). The EPA Inventory follows the guidelines set by the United Nations Framework Convention on Climate Change to produce a common and consistent mechanism for estimating sources and sinks of anthropogenic greenhouse gases that will allow for relative comparisons of different emissions sources (U.S. Environmental Protection Agency, 2016b). The United States signed and ratified the United Nations Framework Convention on Climate Change in 1992, and the EPA has produced its Inventory since 1997. The EPA methodology is consistent with that recommended in the Intergovernmental Panel on Climate Change's "2006 IPCC Guidelines for National Greenhouse Gas Inventories" (Intergovernmental Panel on Climate Change, 2006).

The USGS estimation method differs from the EPA method in scale, scope, and complexity. Calculation of emissions estimates at the scale of Federal lands and individual States is how the USGS process varies the most from the EPA Inventory's methodology. Fine-scale estimates are generally achieved through a bottom-up calculation method; however, the USGS could not obtain State-level data for some parameters. Unavailable inputs were produced by scaling down national-level data from the EPA and EIA. This process is explained in the following sections and in appendix 1.

In terms of scope, the USGS was tasked with investigating the emissions associated with the extraction of fossil fuels on Federal lands and their end-use combustion. Therefore, the USGS estimate is restricted to only the emissions covered in the "Energy" chapter of the EPA Inventory and does not include emissions from agricultural, industrial, or waste-processing activities. Simply stated, the USGS scope discussed in this report is much narrower than that assigned to the EPA. There is, however, one exception: we included an estimate for the end-use combustion emissions of fossil fuels that were produced on Federal lands and exported internationally. As explained in the "Exported Fuels Emissions" section, the emissions from these products are not included in the EPA Inventory.

Emissions estimates provided in the EPA Inventory are the official estimates for the United States and, as such, are produced with annual reviews and refinements by a team of researchers. This USGS study does not strive to improve the EPA's methodology but instead to utilize it. In summary, this USGS estimate borrows heavily from the portion of the EPA method concerning energy-related emissions and is adapted to produce State-level outputs by using inputs specific to Federal lands. The EPA and USGS methods are not competing methods, and the USGS method is not an improvement on any part of the EPA method.

The following sections highlight the general process used to generate the estimates in this study. Because the EPA Inventory served as the main guiding document, this report cites those methods rather than restating them. Introductory information, differences in methods, and process steps that require additional clarification are discussed in the following sections. For specific process steps and tables of data sources, refer to appendix 1.

Stationary Combustion Emissions

Stationary emissions encompass greenhouse gas emissions from the combustion of fossil fuels in nonmobile (nontransportation) sectors. These sectors include the combustion of coal for electricity generation, commercial use, industrial use, and coking coal production. Burning natural gas for electricity generation and the use of natural gas as a feedstock in industrial processes are also included. Refining crude oil to produce liquid fuels used to generate heat or electricity also represents stationary emissions. Various emission factors were used to convert the amounts of fuel combusted into estimates of emissions. Currently, emission factors available in the literature are generally fuel or end-use sector specific. Because of their various uses, the emission factors for stationary combustion of liquid fuel are fuel specific. Emission factors for natural gas and coal are based on the sectors of the economy where the fuels are used. For example, stationary coal combustion emission factors are based on the combustion of mixed ranks of coal in specific sectors of the economy, such as electricity generation versus industrial coking, rather than coal rank, such as the amount of bituminous versus lignite coal used. The use of sector-specific versus rank-specific emission factors allowed the methodology to leverage detailed coal datasets that include annual coal consumption by State of origin and end-use sector (but not by rank) for all coal use in the United States. See appendix 1 for a detailed list of data sources for stationary combustion emissions.

Mobile Combustion Emissions

Calculations of mobile emissions are complicated by the changing technology, efficiency, and total mileage of vehicles driven, flown, and piloted in the United States in any given year. Considering this reality, the USGS method leans heavily on the national emissions calculations included in the EPA Inventory and associated annexes (U.S. Environmental Protection Agency, 2016a, b). The national-level data from the EPA were devolved to ratios of greenhouse gas emissions per gallon of fuel. The ratios were then multiplied by the gallons of fuels that were estimated to have been refined from crude oil produced from Federal lands. The USGS estimate therefore provides emissions estimates for only the fuels that the EPA has estimates for. These are the major fuels—motor gasoline, aviation gasoline, jet kerosene, diesel oil, residual fuel oil, and liquefied petroleum gas—and account for nearly all mobile emissions.

Petroleum and Natural Gas Systems Emissions

This section covers calculations for greenhouse gases released during the extraction and transportation (for example, through pipelines) of natural gas and oil on Federal land, as well as platforms in Federal offshore areas. These types of emissions are generally referred to as fugitive emissions. All fugitive emissions estimates made by the USGS follow a methodology similar to that used for mobile emissions. Because of the complexity involved in determining the emissions from natural gas and oil infrastructure, the USGS relied on the established work of the EPA Inventory rather than attempting to generate the emissions values separately. A ratio of emissions per well, including fugitive emissions from production through distribution for gas and from production through refining for oil, was generated from the EPA Inventory's national emissions estimates (U.S. Environmental Protection Agency, 2016b). This ratio was multiplied by the number of wells producing oil and gas from Federal lands (Bureau of Land Management, written commun., 2016) to estimate the emissions associated with oil and gas infrastructure on those lands. For offshore platforms, the EPA has produced per platform emissions rates that are based on the depth and type of hydrocarbon produced. These rates were used to determine the emissions associated with platforms producing in the Federal offshore Pacific and offshore Gulf areas (U.S. Environmental Protection Agency, 2015).

Active Coal Mine Emissions

Emissions from active coal mines were estimated only for CH_4 at underground and surface mines by using methods outlined in annex 3.4 of the EPA Inventory (U.S. Environmental Protection Agency, 2016a). CH_4 gas is released both during mining and after mining as coal is degassed while in transport and processing. Data for active underground coal mine emissions are collected by the MSHA and reported by mine operators to the EPA Greenhouse Gas Reporting Program. Postmining emissions from underground mines are based on the amount of coal produced from the mine, as well as a basin-specific coal CH_4 content factor. Active surface mine emissions were calculated in a way similar to the postmining emissions from underground coal mines. Postmining emissions from surface mines are based on data collected by the MSHA or reported by mine operators, similar to emissions from active underground mines.

Abandoned Coal Mine Emissions

Even after an underground mine has stopped actively producing coal, the remaining coal releases CH_4 gas for some time. An abandoned mine can be sealed, vented, or flooded as groundwater permeates the mine. The method of abandonment will affect the amount and rate of CH_4 released. In general, mines will release the most CH_4 immediately after abandonment, and the rate will decrease over time. The

rate of decline and the effects of the geology and method of abandonment are explained in the EPA's methodology for estimating abandoned mine emissions (Franklin and others, 2004; U.S. Environmental Protection Agency, 2004). We used a slightly simplified nonprobabilistic version of the method used by the EPA. See appendix 1 for more details on the calculation.

Exported Fuels Emissions

End-use emissions associated with fossil fuels exported from the United States are not included in the EPA Inventory. The Intergovernmental Panel on Climate Change's "2006 IPCC Guidelines for National Greenhouse Gas Inventories" (Intergovernmental Panel on Climate Change, 2006) specified that emissions are counted in the nation where they were emitted; therefore, the EPA includes combustion emissions from imported fuel but not exported fuel. The USGS estimate includes a separate output for emissions from the combustion of fuels produced on Federal lands and exported. However, it is important to note that oil or gas from specific wells or even fields cannot be traced through the U.S. energy system. Coal from some mines may be traceable because of the method of transportation, but those data are not available to the USGS. Therefore, exported fuel amounts were estimated on the basis of national (oil and gas) or State (coal) export data provided by the EIA (U.S. Energy Information Administration, 2015b, 2016a, 2016b). Exported oil, gas, and coal volumes were separated from the gross State production in each of the methods described above. The export volumes were then separately run through the same calculation as the domestic fuel volumes. Essentially, the USGS method calculated a small subset of international emissions. To do this, we assumed that the emission factors in the United States are the same as those in the countries that imported the fuels. Domestic sector proportions specific to each State (if available) and year were the same as those used for the export estimates. These generalized assumptions were necessary because separating the exports by the nations that imported them, determining sector usage proportions for each nation, and using emission factors specific to those nations would amount to an unwarranted level of effort to expend on already estimated export volumes.

Results

The USGS estimates of emissions from the combustion of fossil fuels produced on Federal lands include output values for CO_2, CH_4, and N_2O gases in 28 States, offshore Pacific, and offshore Gulf for the years 2005 through 2014. The results are further segmented by emission category, the sector of the economy, and often, the specific fuel used. Emission categories include stationary combustion, mobile combustion, active coal mining, and others. Examples of sectors include coal used for electricity generation, coal used for industrial applications, diesel oil, natural gas infrastructure, and offgassing from active mines. Because of data availability and method limitations, emissions for each of the three gases were not estimated for all categories, sectors, and fuels. The total numbers of output estimates generated by gas type are 15 for CO_2, 13 for CH_4, and 9 for N_2O. Table 1 contains the USGS emissions estimates for Federal lands in 2014. All results are reported in million metric tons of CO_2 equivalent (MMT CO_2 Eq.). The conversion to CO_2 equivalents enables direct comparison of the different gases. To make the conversion, the amounts of gases are multiplied by their global warming potential, a factor that accounts for the effect a specific gas has in warming the atmosphere relative to the effect of CO_2; the values for the three gases are 1 for CO_2, 25 for CH_4, and 298 for N_2O (Intergovernmental Panel on Climate Change, 2007).

The emissions estimates generated during this study span a 10-year period from 2005 to 2014 and pertain to 30 geographic areas and 37 sector- or fuel-specific outputs. Therefore, the figures and tables presented in this report only summarize the results and are not intended to be a complete presentation of all results. The full dataset is available online at https://doi.org/10.5066/F7KH0MK4 (Merrill and others, 2018). An interactive map is available at https://eerscmap.usgs.gov/fedghg.

Nationwide emissions from fuels extracted from Federal lands in 2014 were 1,279.0 MMT CO_2 Eq. for CO_2, 47.6 MMT CO_2 Eq. for CH_4, and 5.5 MMT CO_2 Eq. for N_2O. The 2014 totals represent decreases in emissions for all three greenhouse gases compared to 2005 values, with reductions of 6.1 percent for CO_2, 10.5 percent for CH_4, and 20.3 percent for N_2O. Total emissions from the production and combustion of fossil fuels produced on Federal lands for the years 2005–14, as well as comparisons to total U.S. emissions, are presented in table 2. On average, Federal lands fuels emissions from 2005 to 2014 accounted for 23.7 percent of national CO_2 emissions, 7.3 percent for CH_4, and 1.5 percent for N_2O (table 2).

In 2014, Wyoming, offshore Gulf, New Mexico, Louisiana, and Colorado had the highest CO_2 emissions from fuels produced on Federal lands (fig. 2). The CO_2 emissions attributed to Federal lands in Wyoming are 57 percent of the total from Federal lands in all States and offshore areas combined. Emissions estimates for the release of CH_4 are also highest for Federal lands in Wyoming (28 percent), followed by New Mexico, offshore Gulf, Colorado, and Utah (fig. 3).

Unsurprisingly, the trends and relative magnitudes of the emissions estimated are roughly parallel to the Federal lands production volumes (U.S. Energy Information Administration, 2015a). States that produced the most fuel from Federal lands are associated with the highest emissions for CO_2, CH_4, and N_2O. These relationships vary slightly relative to absolute production because different fuels require different extraction methods and fuel uses emit varying amounts of greenhouse gases. Trends in emissions over the 10 years of the estimate could indicate changes in production volumes; however, in States where multiple fuels were produced, these relationships may not be evident or direct. Although emission factors, numbers of producing wells, vehicle efficiency, and sector

Table 1. National totals and subtotals for several categories of greenhouse gas emissions associated with the combustion and extraction of fossil fuels from U.S. Federal lands in 2014.

[The full dataset associated with this study (Merrill and others, 2018) contains similar data for 28 States and two offshore areas for 2005–14. For the sector subtotals, the number of significant figures indicates the precision in the underlying State-level estimates. The emissions category totals and Federal lands emissions totals are national totals summed from individual estimates and not the subtotals presented in this table. Therefore, the subtotals listed here may not sum to the national totals. All national totals are reported to one decimal place if greater than 1.0 million metric tons of carbon dioxide equivalent (MMT CO_2 Eq.) or to two significant figures if less than 1.0 MMT CO_2 Eq. CO_2, carbon dioxide; CH_4, methane; N_2O, nitrous oxide; —, values not calculated]

Sector/fuel	CO_2 emissions (MMT CO_2 Eq.)	CH_4 emissions (MMT CO_2 Eq.)	N_2O emissions (MMT CO_2 Eq.)
Combustion emissions from stationary sources			
Coal: electricity generation	725.36	2.09	3.68
Coal: industrial	9.3	0.0268	0.047
Coal: industrial coking	0.016	0.00005	0.00009
Coal: commercial	0.21	0.0006	0.001
Petroleum products	41.77	0.039	0.095
Natural gas	217	0.10	0.12
Stationary total	**993.6**	**2.3**	**3.9**
Combustion emissions from mobile sources			
Motor gasoline	110.892	0.143	1.239
Aviation gasoline	0.3	—	—
Jet kerosene	25.58	—	—
Diesel oil	58.25	—	0.06
Residual fuel oil	4.61	—	—
Liquefied petroleum gas	0.078	—	—
Mobile total	**199.7**	**0.14**	**1.3**
Extraction emissions from petroleum and natural gas systems			
Petroleum wells, equipment, and platforms	0.18	7.97	—
Natural gas wells, equipment, and platforms	5.3	25.31	—
Extraction emissions from coal mining			
Surface mines	—	4.34	—
Underground mines	—	6.20	—
Abandoned mines	—	1.22	—
Coal mining total	**—**	**11.8**	**—**
Total emissions from Federal lands			
Domestic	1,198.8	47.5	5.2
Exported	80.2	0.10	0.27
Total Federal lands	**1,279.0**	**47.6**	**5.5**

Table 2. National totals for greenhouse gas emissions associated with the combustion and extraction of fossil fuels from U.S. Federal lands in 2005–14.

[CO_2, carbon dioxide; CH_4, methane; NO_2, nitrous oxide; MMT CO_2 Eq., million metric tons of carbon dioxide equivalent]

Year	CO_2 emissions		CH_4 emissions		N_2O emissions	
	Federal lands fossil fuels (MMT CO_2 Eq.)	Percentage of U.S. total[1]	Federal lands fossil fuels (MMT CO_2 Eq.)	Percentage of U.S. total[1]	Federal lands fossil fuels (MMT CO_2 Eq.)	Percentage of U.S. total[1]
2005	1,361.9	22.2	53.2	7.4	6.9	1.7
2006	1,378.6	22.8	53.4	7.4	6.8	1.7
2007	1,398.3	22.8	53.8	7.4	6.4	1.5
2008	1,427.9	24.1	55.8	7.6	6.5	1.6
2009	1,422.5	25.9	53.4	7.3	6.7	1.7
2010	1,429.4	25.1	53.3	7.4	6.6	1.6
2011	1,362.4	24.5	55.7	7.8	6.2	1.5
2012	1,280.5	23.9	52.0	7.3	5.7	1.4
2013	1,210.5	22.0	48.8	6.8	5.4	1.3
2014	1,279.0	23.0	47.6	6.5	5.5	1.4

[1]Percentages calculated from total U.S. emissions (U.S. Environmental Protection Agency, 2016b).

usage rates all change from year to year, they have minimal effect on the final emissions results compared to the amount of fossil fuel production. Any significant changes in production will result in a similar change in the attributed emissions. Federal lands fuels production by State (U.S. Energy Information Administration, 2015a) is therefore very similar in relative magnitude to the emissions results presented in this report.

Uncertainty of Emissions Estimates

The emissions estimates in this report do not include estimates of uncertainty. Calculated uncertainties provided in the annexes to the EPA Inventory (U.S. Environmental Protection Agency, 2016a, annex 7) are informative and presumed to be applicable because the USGS employed a slightly modified EPA methodology. In summary, the EPA determined that the emissions estimate uncertainty was smaller for combustion calculations than uncertainties for fugitive emissions from extractive activities. This difference in uncertainties is intuitive because combusted materials are measured for sale and therefore are well constrained, whereas the amounts of gases emitted from extraction are often estimated or scaled up from smaller sampling efforts. For example, the annexes to the EPA Inventory (U.S. Environmental Protection Agency, 2016a, annex 7) cited uncertainty with a 95-percent confidence interval from −2 to 5 percent of the 2014 mean CO_2 emissions from fossil fuel combustion. In contrast, nonenergy CO_2 emissions uncertainties ranged from −25 to 42 percent. Uncertainties for CH_4 emitted by coal mining ranged from −12 to 15 percent. Overall, owing to the significant proportion of emissions tied to the combustion of fossil fuels, the total uncertainty of the EPA Inventory estimate was between −2 and 5 percent.

Precision and Rounding of Emissions Estimates

The emissions estimates summarized in this report and provided in the associated dataset (Merrill and others, 2018) were formatted in an effort to indicate their precision. For all nontotal values, meaning those estimates that represent a single sector, gas, State, and year combination, the number of significant figures indicates the level of precision inherent in the calculations that generated that number. In the calculations used to generate the estimates, accurate but less precise sector ratios or emission factors are commonly the parameters with the least precision, and they limit the estimate's precision.

For the convenience of the reader, this report and the associated dataset include totals for grouped sectors such as stationary combustion, mobile combustion, and coal mine fugitive emissions. Totals for domestic, exported, and overall total emissions are also included. These totals are formatted in a specific way to capture the 12 orders of magnitude in range present in the various estimates of this dataset. Totals greater than or equal to 1.0 MMT CO_2 Eq. are rounded to the first decimal place, whereas values less than 1.0 MMT CO_2 Eq. are shown with two significant figures. This method of representing the estimates, used only for totals, facilitates the comparison of emissions totals that are below 1.0 MMT CO_2 Eq.

Performing calculations on the rounded total values, such as summing State total emissions rather than all individual sector emissions, to obtain national emissions will incur and possibly compound rounding errors. Users of the dataset are advised to perform calculations on the individual values rather than the rounded totals. All totals in this report were calculated from the underlying individual estimate values and are deemed accurate; the totals are not summations of subtotals.

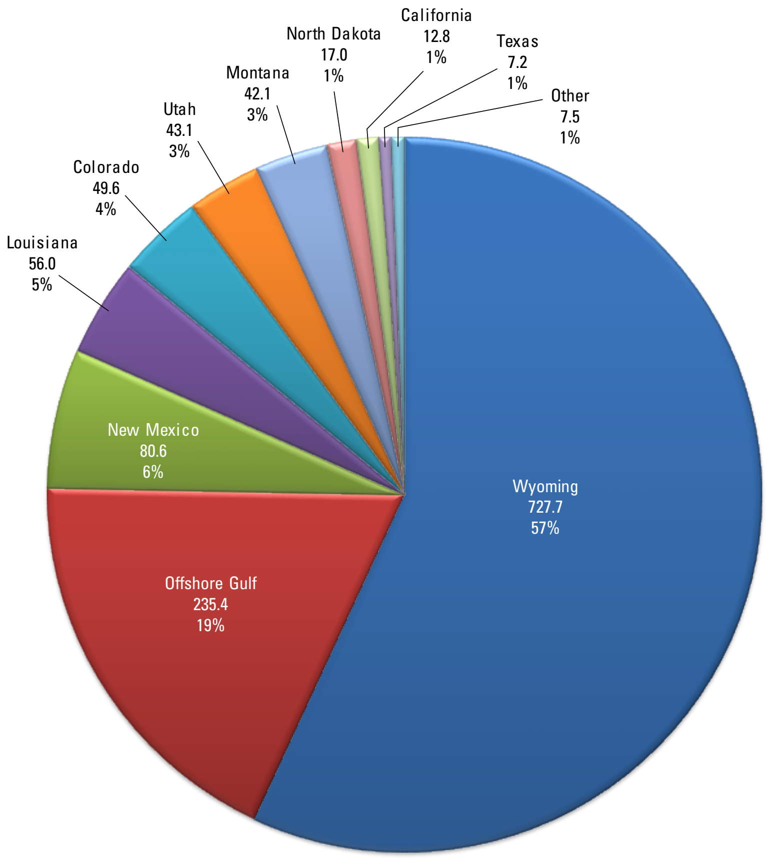


Figure 2. Pie chart showing carbon dioxide emissions associated with the extraction and combustion of fossil fuels produced from Federal lands in the 10 States or offshore regions with the highest emissions, 2014. Emissions are reported in million metric tons of carbon dioxide equivalent (MMT CO_2 Eq.).

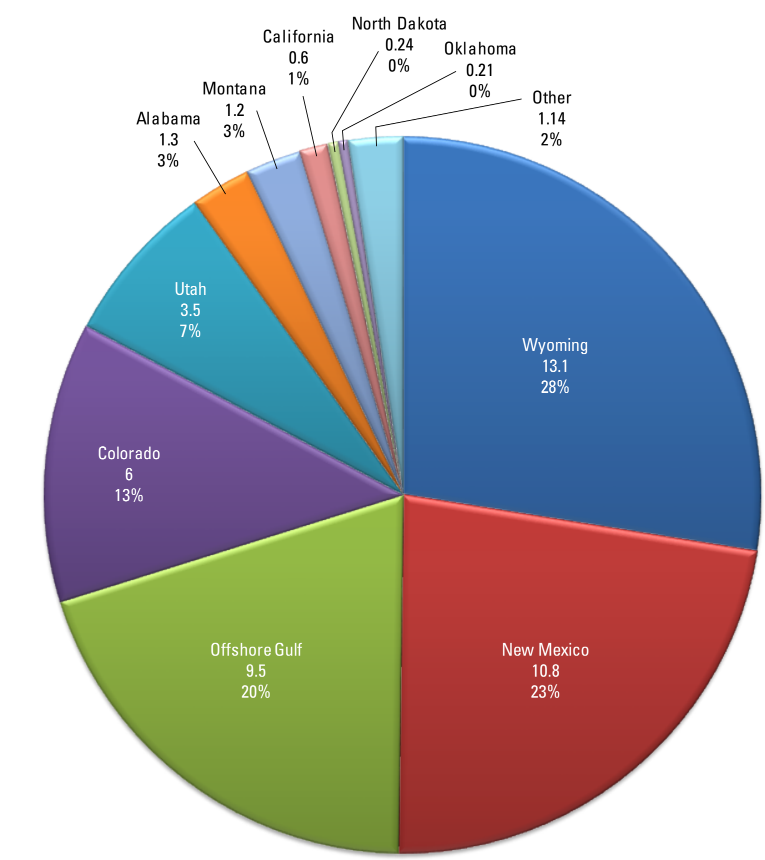


Figure 3. Pie chart showing methane emissions associated with the extraction and combustion of fossil fuels produced from Federal lands in the 10 States or offshore regions with the highest emissions, 2014. Emissions are reported in million metric tons of carbon dioxide equivalent.

Terrestrial Ecosystems-Associated Carbon Emissions and Sequestration on Federal Lands

Introduction

For the ecosystems emissions and sequestration portion of the USGS study, we estimated the annual amount of CO_2 that was stored and emitted by terrestrial ecosystems, including forests, grasslands, shrublands, and agricultural lands. Plants convert CO_2 to carbon through photosynthesis, which is expressed as gross primary productivity (GPP). See table 3 for a summary of the terms introduced in this section. The terms include stocks, the amount of carbon present in a carbon reservoir, and fluxes, annual changes to those stocks that can be additions (sequestration) or removals (emissions). Autotrophic respiration (Ra) is the release of CO_2 back to the atmosphere by plants through respiration. The difference between GPP and Ra is referred to as net primary productivity (NPP), or the amount of CO_2 fixed or stored in new vegetation each year. Ecosystems also respire CO_2 through the decay and decomposition of dead organic matter (DOM), referred to as heterotrophic respiration (Rh). The total net ecosystems productivity (NEP) can thus be estimated as GPP − (Ra + Rh).

Changes to ecosystems, typically caused by wildfires (fire) and forest harvest (harvest), are considered forms of land-use and land-use and land-cover (LULC) change. Other forms of LULC change, including agricultural harvesting, are grouped in a separate category in this study (other). These changes typically result in the removal of carbon from the ecosystem and are therefore considered emissions for the purpose of this study. Ecosystem carbon losses associated with land use and land-use change and disturbance are subtracted from NEP to estimate net biome productivity (NBP), which reflects the absolute change in carbon stored within ecosystems on an annual basis. NBP is an appropriate value for comparison with annual fossil fuel-associated emissions and is used again in this report where the concept of net emissions is introduced. In the full dataset associated with this study (Merrill and others, 2018), we provide estimates of most of the stocks and fluxes in table 3. Estimates are included for carbon stocks such as TEC, Live, DOM, and Soil and annual carbon fluxes such as Rh, NPP, NEP, NBP, fire, harvest, and other for Federal lands of the United States for the period 2005–14.

Data Sources

This USGS study used three main sources to estimate the carbon balance on Federal lands of the United States. For the conterminous United States (CONUS), we analyzed the results of net ecosystem carbon fluxes produced by a dynamic global vegetation model. For the State of Hawaii, we estimated ecosystem carbon balance by using a look-up table approach based on results from a recent USGS assessment of carbon storage and fluxes (Selmants and others, 2017). The net carbon balance for Alaska was estimated from another recent USGS assessment (Zhu and McGuire, 2016). These three existing sources contain estimates that span different ranges of years, all longer than the span of this study; however, the results from those additional years are not included in this report or the associated dataset because they do not match the study period for the fossil fuel-associated estimates (2005–14). Here we provide an overview of the sources used to estimate the net carbon balance on Federal lands. Additional details are provided in appendix 2.

We estimated carbon balance on Federal lands of the CONUS by analyzing spatially explicit maps of net carbon fluxes produced by using a process-based dynamic global vegetation model (Liu and others, 2016). Carbon stock and flux maps were estimated by using the Integrated Biosphere Simulator (IBIS) model (Foley and others, 1996; Kucharik and others, 2000). The IBIS model was used to estimate changes in carbon stocks and fluxes for the period 1970–2015 at approximately 1-kilometer (km) x 1-km resolution for all forests, grasslands, shrublands, wetlands, and agricultural land areas within the CONUS. Annual maps of carbon stocks and fluxes were combined with maps of Federal lands to produce annual estimates of carbon balance by State for the 45-year period.

Carbon fluxes for the State of Hawaii were derived through an analysis of data produced in support of the USGS biological carbon sequestration assessment for the State (Selmants and others, 2017). The assessment included estimates of carbon stocks and fluxes for forests, grasslands, and shrublands across three moisture zones (dry, mesic, and wet). Average annual carbon stock and flux densities were developed for the current study and applied to the State's Federal land area.

For Alaska, estimates of ecosystem carbon dynamics were based on the USGS biological carbon sequestration assessment for the State (Zhu and McGuire, 2016). The Alaska assessment yielded estimates of carbon stocks and fluxes from uplands and wetlands across a baseline period of 1950–2010. The Alaska assessment produced a set of mean annual carbon stock and flux maps for the period 2001–10 that were used to estimate the average carbon balance of Alaska's Federal lands.

Methodology

Because of differences in existing work, calculation model structure, and data availability, the estimates of ecosystems carbon emissions and sequestration were prepared separately for the CONUS, Alaska, and Hawaii. The CONUS analysis was based on simulations that used the IBIS model (Liu and others, 2016). The Alaska data were modified from existing work by Zhu and McGuire (2016), and the Hawaii results were modified from Selmants and others (2017). The methodologies behind these three estimates are discussed briefly here and with more detail in appendix 2.

Table 3. Explanation of carbon stock and flux terms from the terrestrial ecosystem sequestration calculations.

[Terms are grouped by carbon stock or typical flux type. This table may be useful in viewing the results in tables 4 and 5. CO_2, carbon dioxide]

Term	Name	Explanation
		Stocks: terrestrial carbon reservoirs
TEC	Total ecosystem carbon	Total carbon stored in an ecosystem; the combination of carbon stored in soils, DOM, and live vegetation.
Live	Live vegetation	Carbon stored in live vegetation, both above and below ground.
Soil	Soil organic matter	Carbon stored in the organic material of soils.
DOM	Dead organic matter	Carbon stored in dead organic matter.
		Fluxes: carbon sequestration
GPP	Gross primary productivity	CO_2 removed from the atmosphere and converted to carbon by plant photosynthesis.
NPP	Net primary productivity	The difference between GPP and Ra. The amount of CO_2 fixed or stored in new vegetation each year.
NEP	Net ecosystems productivity	GPP − (Ra + Rh)
NBP	Net biome productivity	Ecosystems carbon losses caused by land-use and land-cover change and disturbances. The absolute change in carbon stored within ecosystems.
		Fluxes: carbon emissions
Ra	Autotrophic respiration	CO_2 released to the atmosphere by plant respiration.
Rh	Heterotrophic respiration	CO_2 released to the atmosphere from decay of DOM
Fire	Wildfire carbon flux	Ecosystem carbon loss as CO_2 released to the atmosphere during wildfire.
Harvest	Forest harvest carbon flux	Ecosystem carbon loss from forest timber harvest.
Other	Other land-use/land-cover changes	Ecosystem carbon loss from land use (agricultural harvest) and land-use/land-cover change other than fire and timber harvest.

Conterminous United States

We estimated carbon stocks and fluxes in the CONUS by using the IBIS model (Foley and others, 1996; Kucharik and others, 2000). We used a modified version of the IBIS model that includes nitrogen controls on the carbon cycle (Liu and others, 2005), LULC change, wildland fire effects (Liu and others, 2011, 2016), and CH_4 emissions (Zhu and others, 2014).

IBIS includes 11 types of disturbances: (1) fire, (2) logging, (3) deforestation to grasslands and shrublands, (4) deforestation to cropland, (5) afforestation from grasslands and shrublands, (6) afforestation from agriculture, (7) urbanization from forest, (8) urbanization from grasslands and shrublands, (9) urbanization from cropland, (10) agricultural expansion from grassland and shrublands, and (11) agricultural contraction (cropland converting to grasslands and shrublands). Logging and fire events trigger carbon removal and tree mortality without changing the forest-cover fraction, allowing for forest regrowth. Other types of disturbance remove carbon from the landscape and alter land cover fractions. For example, the forest to cropland transition (deforestation) will reallocate the previous forest-cover fraction to the cropland-cover fraction and remove all forest carbon from the landscape. As a result, the following simulation year will have no forest productivity but more crop productivity owing to the increase in the cropland-cover fraction. Other disturbance types, such as insect-induced mortality, disease, and wind and weather, were not included in this study.

Federal lands in the CONUS were identified from the USGS Protected Areas Database of the United States (PADUS) version 1.4 (U.S. Geological Survey, 2016). A mask was created by selecting all PADUS polygons that had a Federal owner designation. These included lands managed by the Bureau of Land Management, U.S. Forest Service, U.S. Department of Defense, U.S. Department of Energy, Bureau of Reclamation, U.S. Army Corps of Engineers, National Park Service, National Oceanic and Atmospheric Administration, Natural Resources Conservation Service, and other Federal agencies. American Indian Lands and Tribal lands were not included in this analysis. Within the Federal lands mask, all coastal and offshore areas were excluded. The Federal lands layer was then aggregated to a single binary map and combined with U.S. State boundaries from the U.S. Census Bureau (https://www.census.gov/geo/maps-data/data/cbf/cbf_state.html) to provide a unique State identification code for each Federal land cell. All processing was done at a spatial resolution of 960 meters (m) x 960 m using an Albers Equal-Area Conic projection. Although small changes in the extent of Federal lands may have taken place over the period of study, we assumed that the extent of Federal lands was unchanging over time.

We used the Federal lands mask described above to extract seven key IBIS carbon stock and flux variables: NPP, NEP, NBP, total ecosystem carbon (TEC) stock, live vegetation carbon stock, emissions associated with wildfire, and carbon removals associated with LULC change. The IBIS output data consist of annual maps of each carbon stock and flux variable at 960-m x 960-m resolution. Each map was stored as a multilayer Network Common Data Form file with each layer representing a single year between 1971 and 2015. Processing of all data was done by using the raster package (Hijmans and van Etten, 2012) of the R statistical package (R Core Team, 2013). Each of the seven IBIS-variable Network Common Data Form files was imported into R as a multilayer raster brick object, and the coordinate reference system and spatial extents were defined. Next, we extracted carbon values for Federal lands by using the Federal lands mask, and the zonal function was used to calculate the mean carbon density in kilograms per square meter for each State in each year. To estimate the total carbon value for all Federal land cells within a State, we first calculated the total number of cells with valid data extracted by the Federal lands mask and then calculated the total area in square meters for each State. The total areas were then multiplied by the carbon densities and divided by 1 billion to produce estimates of million metric tons of carbon. The carbon values were then multiplied by 3.67 to convert to million metric tons of CO_2. To facilitate comparisons with the fossil fuel-associated emissions estimates and EPA Inventory estimates, all carbon stocks and sequestration are represented as negative values and all carbon releases or losses to the atmosphere are represented as positive values.

Alaska

Estimates of ecosystem carbon dynamics in Alaska were based on the USGS biological carbon sequestration assessment for the State of Alaska (Zhu and McGuire, 2016). For the Alaska assessment, researchers estimated carbon stocks and fluxes from uplands and wetlands across a baseline period spanning 1950–2010. For both uplands and wetlands, the Dynamic Organic Soil version of the Terrestrial Ecosystem Model (DOS-TEM; Genet and others, 2013) was used to estimate carbon stocks and fluxes for 1-km x 1-km simulation cells. Soil and vegetation carbon estimates from DOS-TEM were validated against a range of in situ data collected across a range of ecosystem types. For more detail on the Alaska ecosystem modeling, see Zhu and McGuire (2016).

To estimate carbon stocks and fluxes for Federal lands in Alaska, we used spatially explicit output from DOS-TEM at 1-km spatial resolution. Spatially explicit decadal averages of five carbon parameters were obtained from the Scenarios Network for Alaska and Arctic Planning at http://ckan.snap.uaf.edu. Carbon flux parameters include mean annual NPP, Rh, and carbon losses owing to fire. Additionally, carbon stock estimates for soil and live vegetation were available. First, we calculated NEP by subtracting Rh from NPP. Because of data limitations, wildfire was the only carbon loss considered when estimating NBP, which was calculated by subtracting the burn map carbon losses from the calculated NEP map. Next, all carbon maps were spatially subset to include only Federal lands. Mean decadal carbon stocks and fluxes were then added as a stationary input to the annual totals calculated for the CONUS.

Hawaii

Carbon stocks and fluxes for the State of Hawaii were estimated on the basis of an analysis of the USGS biological carbon sequestration assessment for the State of Hawaii (Selmants and others, 2017). For the Hawaii assessment, researchers estimated mean annual carbon stocks and fluxes for forests, grasslands, and shrublands across three moisture zones (dry, mesic, wet) for the period 2001–16 (Sleeter and others, 2017) by using the Land Use and Carbon Scenario Simulator (LUCAS) model. The LUCAS model included estimates and projections of the effects of land-use change, wildfire, and future changes in moisture zones on the carbon balance of terrestrial ecosystems. The LUCAS model was run in a spatially referenced mode, and spatially explicit maps of carbon stocks and fluxes were not produced.

Live vegetation and soil organic carbon (to 1-m depth) stocks for the seven main Hawaiian Islands containing Federal lands (Hawaii, Maui, Lanai, Kahoolawe, Molokai, Oahu, and Kauai) were estimated from spatially explicit maps developed for the USGS biological carbon sequestration assessment (Selmants and others, 2017). We then summarized the total carbon storage by intersecting the live vegetation and soil organic carbon maps with a map of Federal lands.

To estimate carbon fluxes for Federal lands in Hawaii, we extracted statewide total carbon estimates for the period 2005–15 from a “no-change” scenario (where no changes in land use, fire, or climate were considered). Carbon densities were calculated on the basis of the distribution of the combinations of LULC classes (forest, grassland, shrubland) and moisture zones (dry, mesic, wet), which were assumed to be fixed through time. Next, we calculated the area of each LULC class type for the Federal lands of Hawaii by intersecting an LULC map (Jacobi and others, 2017) with a map of Federal lands extracted from the PADUS dataset. Lastly, we applied the State-level carbon densities to the Federal lands area to estimate carbon stocks and fluxes. It is important to note that because LULC change and disturbances were not considered, only NPP, Rh and NEP were estimated for Hawaii.

Results

The carbon sequestration results were calculated for various timeframes depending on geographic area and specific output. For comparison with the fossil fuel-associated emissions, the following results are provided for the years 2005–14 only. In 2005, Federal lands of the CONUS stored 82,289 MMT CO_2 Eq. in terrestrial ecosystems (TEC). By

2014, carbon storage was estimated at 83,600 MMT CO_2 Eq., representing an increase of 1.6 percent, or 1,311 MMT CO_2 Eq. Soils stored most of the TEC (63 percent), followed by live vegetation (26 percent) and DOM (10 percent). Over the 10-year period, 400 MMT CO_2 Eq. was sequestered in live vegetation, 478 MMT CO_2 Eq. was sequestered in soils, and 433 MMT CO_2 Eq. was added to DOM pools. Average carbon storage in live vegetation and soils in Alaska was estimated at 131,675 MMT CO_2 Eq., with 92 percent stored in soils (120,618 MMT CO_2 Eq.) and 8 percent stored in live vegetation (11,057 MMT CO_2 Eq.). For the State of Hawaii, we estimated 24 MMT CO_2 Eq. was stored in live vegetation and 51 MMT CO_2 Eq. was stored in soils. On average, terrestrial ecosystems stored a combined 214,554 MMT CO_2 Eq. on Federal lands between 2005 and 2014 (table 4).

Between 2005 and 2014, Federal lands sequestered an average of 343 million metric tons of carbon dioxide equivalent per year (MMT CO_2 Eq./yr) (annual NEP), the difference between an average gain through NPP of 2,567 MMT CO_2 Eq./yr and an average loss through ecosystem Rh of 2,224 MMT CO_2 Eq./yr. Additional losses of carbon from terrestrial ecosystems resulted from wildfire (21 MMT CO_2 Eq./yr in the CONUS and 46 MMT CO_2 Eq./yr in Alaska), logging (43 MMT CO_2 Eq./yr), and other land use and land-use changes (39 MMT CO_2 Eq./yr). By subtracting the cumulative effects of LULC- and disturbance-related CO_2 losses to the atmosphere from the NEP, we estimated that ecosystems at the national level sequestered CO_2 at a mean rate of 195 MMT CO_2 Eq./yr (NBP). The amount of CO_2 sequestered offset approximately 15 percent of the CO_2 emissions resulting from the extraction of fossil fuels on Federal lands and their end-use combustion. Federal lands in the CONUS accounted for most of the net carbon sink (177 MMT CO_2 Eq./yr), and Alaska accounted for the remainder.

Carbon sequestration on Federal lands was highly variable over time, owing primarily to interannual variability in climate and weather, long-term increases in CO_2 fertilization, and variability in LULC and disturbances (fig. 4). Between 2005 and 2014, NPP in the CONUS ranged from 1,841 to 2,283 MMT CO_2 Eq./yr. Over the same period, NBP varied between sequestering 475 MMT CO_2 Eq./yr and emitting carbon to the atmosphere at a rate of 51 MMT CO_2 Eq./yr. The large variation in the size of the land sink was due, in part, to variability in the magnitude of disturbances. For example, emissions from wildfire in the CONUS ranged from 3 MMT CO_2 Eq./yr in 2014 to 44 MMT CO_2 Eq./yr in 2012. Over the full period of the simulations (1970–2015), variability was even higher (fig. 4).

On average, Federal lands in the State of Alaska stored 131,675 MMT CO_2 Eq., with 92 percent stored in soils (120,618 MMT CO_2 Eq.) and 8 percent stored in live vegetation (11,057 MMT CO_2 Eq.). The amount of carbon stored on Federal lands in Alaska was approximately 62 percent of the total carbon stored on Federal lands, indicating Alaska's importance in the overall U.S. carbon balance. Nine States accounted for over 60 percent of the carbon storage on Federal lands in the CONUS (table 5). The largest amount was stored in Oregon, followed by California, Idaho, Montana, Nevada, Wyoming, Colorado, Washington, and Utah. Oregon stored 10.9 percent (8,985 MMT CO_2 Eq.) of the

Table 4. Carbon stocks and fluxes for Federal lands in the conterminous United States, 2005–14.

[Units are in million metric tons of carbon dioxide equivalent for stocks and million metric tons of carbon dioxide equivalent per year for fluxes. Because of rounding, averages may not add to totals shown. Negative values indicate a net carbon sink or sequestration, and positive values indicate a net carbon source to the atmosphere or emissions. Total U.S. values can be approximated by adding the average stocks and fluxes in Alaska and Hawaii (table 5) to the values presented here. TEC, total ecosystem carbon; Live, storage in live vegetation; DOM, storage in dead organic matter; Soil, storage in soils; NPP, net primary productivity; Rh, heterotrophic respiration; NEP, net ecosystems productivity; NBP, net biome productivity; Fire, carbon emissions from wildfire; Harvest, carbon loss from forest harvest; Other, carbon loss from land-use and land-cover change and harvested agricultural products. See table 3 and the text for further explanation of carbon stocks and fluxes]

Year	Carbon stocks				Carbon fluxes						
	TEC	Live	DOM	Soil	NPP	Rh	NEP	NBP	Fire	Harvest	Other
2005	−82,289	−21,270	−8,533	−52,486	−2,283	1,708	−575	−475	11	55	34
2006	−82,322	−21,090	−8,698	−52,534	−1,870	1,723	−147	−29	24	53	40
2007	−82,275	−20,889	−8,779	−52,607	−1,841	1,759	−83	51	34	53	46
2008	−82,353	−20,810	−8,870	−52,673	−1,854	1,661	−193	−75	24	56	38
2009	−82,605	−21,006	−8,875	−52,725	−2,038	1,687	−350	−249	9	59	34
2010	−82,951	−21,310	−8,871	−52,770	−2,174	1,734	−440	−342	9	55	34
2011	−83,170	−21,365	−8,982	−52,823	−1,986	1,686	−301	−219	19	25	38
2012	−83,139	−21,233	−9,033	−52,872	−1,875	1,786	−89	31	44	24	52
2013	−83,334	−21,392	−9,023	−52,919	−2,076	1,783	−293	−195	30	25	43
2014	−83,600	−21,670	−8,966	−52,964	−2,119	1,796	−323	−265	3	25	30
Average	−82,804	−21,204	−8,863	−52,737	−2,012	1,732	−279	−177	21	43	39

Table 5. Average annual carbon stocks and fluxes for onshore Federal lands in the United States, 2005–14.

[Units are in million metric tons of carbon dioxide equivalent for stocks and million metric tons of carbon dioxide equivalent per year for fluxes. Negative values indicate a net carbon sink, and positive values indicate a net carbon source to the atmosphere. TEC, total ecosystem carbon; Live, storage in live vegetation; DOM, storage in dead organic matter; Soil, storage in soils; NPP, net primary productivity; Rh, heterotrophic respiration; NEP, net ecosystems productivity; NBP, net biome productivity; Fire, carbon emissions from wildfire; Harvest, carbon loss from forest harvest; Other, carbon loss from land-use/land-cover change and harvested agricultural products, —, value not calculated. See table 3 and the text for further explanation of carbon stocks and fluxes.]

State	Carbon stocks				Carbon fluxes						
	TEC	Live	DOM	Soil	NPP	Rh	NEP	NBP	Fire	Harvest	Other
Alabama	−427.6	−201.0	−36.7	−190.0	−20.3	16.6	−3.7	−1.8	0.2	1.3	0.4
Alaska	−131,675	−11,057	—	−120,618	−552	489	−64	−18	46	—	—
Arizona	−2,129.2	−466.4	−207.1	−1,455.7	−55.3	55.5	0.2	1.9	0.7	0.3	0.7
Arkansas	−773.1	−385.6	−70.9	−316.6	−25.6	20.3	−5.3	−2.5	0.2	1.9	0.8
California	−8,387.3	−2,822.4	−1,179.7	−4,385.2	−255.9	225.2	−30.7	−14.5	5.1	2.9	8.2
Colorado	−4,363.0	−1,007.3	−481.9	−2,873.8	−96.3	79.7	−16.6	−13.8	0.4	0.5	1.9
Connecticut	−5.8	−1.2	−0.5	−4.1	−0.1	0.1	0.0	0.0	0.0	0.0	0.0
Delaware	−44.7	−4.6	−1.4	−38.6	−0.6	0.5	−0.1	0.0	0.0	0.0	0.0
District of Columbia	−11.0	−3.3	−1.1	−6.6	−0.3	0.3	0.0	0.0	0.0	0.0	0.0
Florida	−2,546.9	−267.9	−117.6	−2,161.5	−46.0	42.8	−3.2	−0.1	1.2	0.7	1.1
Georgia	−1,636.9	−358.5	−83.9	1,194.5	−33.3	29.0	−4.3	−2.2	0.3	1.2	0.6
Hawaii	−75	−24	—	−51	−3	3	<−1	—	—	—	—
Idaho	−7,520.5	−1,866.6	−943.1	−4,710.8	−164.2	138.6	−25.6	−14.0	4.3	2.3	4.9
Illinois	−242.4	−94.5	−22.0	−125.9	−9.0	7.3	−1.7	−0.7	0.0	0.2	0.8
Indiana	−252.3	−106.8	−25.3	−120.2	−9.7	7.9	−1.8	−1.1	0.0	0.3	0.3
Iowa	−46.8	−8.1	−2.1	−36.6	−0.9	0.6	−0.3	−0.1	0.0	0.0	0.2
Kansas	−94.4	−7.3	−2.8	−84.3	−2.7	2.0	−0.7	0.0	0.1	0.0	0.6
Kentucky	−677.2	−320.2	−65.9	−291.2	−27.6	22.8	−4.8	−3.0	0.0	1.3	0.5
Louisiana	−513.6	−135.1	−23.4	−355.1	−14.4	12.2	−2.2	−0.5	0.2	1.2	0.3
Maine	−75.2	−17.9	−5.8	−51.5	−1.7	1.4	−0.3	−0.2	0.0	0.1	0.0
Maryland	−57.8	−11.4	−3.1	−43.2	−1.2	1.1	−0.2	−0.1	0.0	0.0	0.0
Massachusetts	−34.7	−4.8	−2.4	−27.5	−0.6	0.5	−0.1	0.0	0.0	0.0	0.0
Michigan	−3,194.8	−432.6	−255.4	−2,506.8	−44.5	38.9	−5.6	−3.9	0.0	1.2	0.5
Minnesota	−2,438.7	−312.4	−137.4	−1,988.9	−31.8	28.5	−3.3	−1.8	0.2	0.6	0.6
Mississippi	−659.5	−279.5	−55.8	−324.2	−31.0	25.9	−5.1	−1.7	0.4	1.9	1.0
Missouri	−705.1	−319.3	−68.3	−317.5	−20.9	16.8	−4.1	−2.4	0.1	0.7	1.0
Montana	−6,141.4	−1,768.7	−813.2	−3,559.5	−167.2	143.8	−23.5	−18.9	1.4	2.1	1.2
Nebraska	−152.7	−17.3	−9.5	−125.9	−3.6	3.1	−0.5	−0.3	0.0	0.0	0.2
Nevada	−4,882.2	−712.3	−525.7	−3,644.1	−109.2	105.1	−4.1	−0.5	1.0	0.6	2.1

Table 5. Average annual carbon stocks and fluxes for onshore Federal lands in the United States, 2005–14.—Continued

[Units are in million metric tons of carbon dioxide equivalent for stocks and million metric tons of carbon dioxide equivalent per year for fluxes. Negative values indicate a net carbon sink, and positive values indicate a net carbon source to the atmosphere. TEC, total ecosystem carbon; Live, storage in live vegetation; DOM, storage in dead organic matter; Soil, storage in soils; NPP, net primary productivity; Rh, heterotrophic respiration; NEP, net ecosystems productivity; NBP, net biome productivity; Fire, carbon emissions from wildfire; Harvest, carbon loss from forest harvest; Other, carbon loss from land-use/land-cover change and harvested agricultural products, —, value not calculated. See table 3 and the text for further explanation of carbon stocks and fluxes.]

State	Carbon stocks				Carbon fluxes						
	TEC	Live	DOM	Soil	NPP	Rh	NEP	NBP	Fire	Harvest	Other
New Hampshire	−320.6	−120.2	−39.3	−161.2	−10.0	8.5	−1.5	−1.1	0.0	0.4	0.0
New Jersey	−142.0	−16.8	−6.5	−118.8	−1.9	1.7	−0.2	−0.2	0.0	0.0	0.0
New Mexico	−2,299.8	−530.6	−265.5	−1,503.7	−64.5	60.8	−3.7	−2.1	0.7	0.3	0.6
New York	−96.7	−23.1	−6.5	−67.1	−2.0	1.6	−0.3	−0.2	0.0	0.0	0.1
North Carolina	−2,906.8	−519.1	−123.9	−2,263.8	−46.2	39.1	−7.1	−4.5	0.1	1.8	0.7
North Dakota	−491.1	−35.2	−18.6	−437.4	−12.8	9.9	−2.9	−1.8	0.0	0.0	1.0
Ohio	−249.5	−116.2	−22.5	−110.8	−9.4	7.6	−1.8	−0.9	0.0	0.5	0.4
Oklahoma	−199.3	−55.5	−12.2	−131.5	−6.7	5.6	−1.1	−0.3	0.0	0.4	0.3
Oregon	−8,985.2	−2,685.8	−1,054.4	−5,245.0	−198.9	159.5	−39.4	−29.6	1.3	6.7	1.8
Pennsylvania	−247.9	−114.6	−24.8	−108.5	−8.2	6.6	−1.6	−1.2	0.0	0.3	0.1
Rhode Island	−16.0	−5.2	−1.9	−9.0	−0.4	0.4	−0.1	0.0	0.0	0.0	0.0
South Carolina	−532.8	−187.3	−39.1	−306.5	−18.8	15.9	−2.9	−1.1	0.2	1.2	0.4
South Dakota	−596.5	−102.0	−59.6	−434.9	−17.0	14.0	−3.1	−2.5	0.0	0.1	0.4
Tennessee	−586.9	−283.6	−58.8	−244.5	−23.2	19.8	−3.4	−2.3	0.1	0.6	0.5
Texas	−786.4	−199.1	−39.2	−548.0	−22.6	19.6	−3.0	−0.7	0.2	1.2	0.9
Utah	−3,581.9	−706.5	−358.4	−2,517.1	−82.8	72.0	−10.8	−8.6	0.5	0.4	1.3
Vermont	−375.6	−94.9	−32.2	−248.5	−8.2	6.9	−1.3	−0.9	0.0	0.4	0.1
Virginia	−1,255.8	−513.1	−118.2	−624.5	−45.9	39.4	−6.5	−4.2	0.1	1.4	0.7
Washington	−4,248.7	−1,703.2	−582.4	−1,963.0	−104.2	80.2	−24.0	−18.2	0.9	4.2	0.7
West Virginia	−651.8	−279.1	−69.6	−303.1	−23.7	20.1	−3.6	−2.5	0.0	0.9	0.2
Wisconsin	−1,405.1	−163.1	−75.9	−1,166.1	−16.6	14.9	−1.7	−1.1	0.0	0.4	0.2
Wyoming	−4,812.2	−816.0	−711.1	−3,285.1	−113.8	101.7	−12.1	−10.4	0.5	0.6	0.6
United States	−214,554	−32,285	−8,863	−173,406	−2,567	2,224	−343	−195	67	43	39

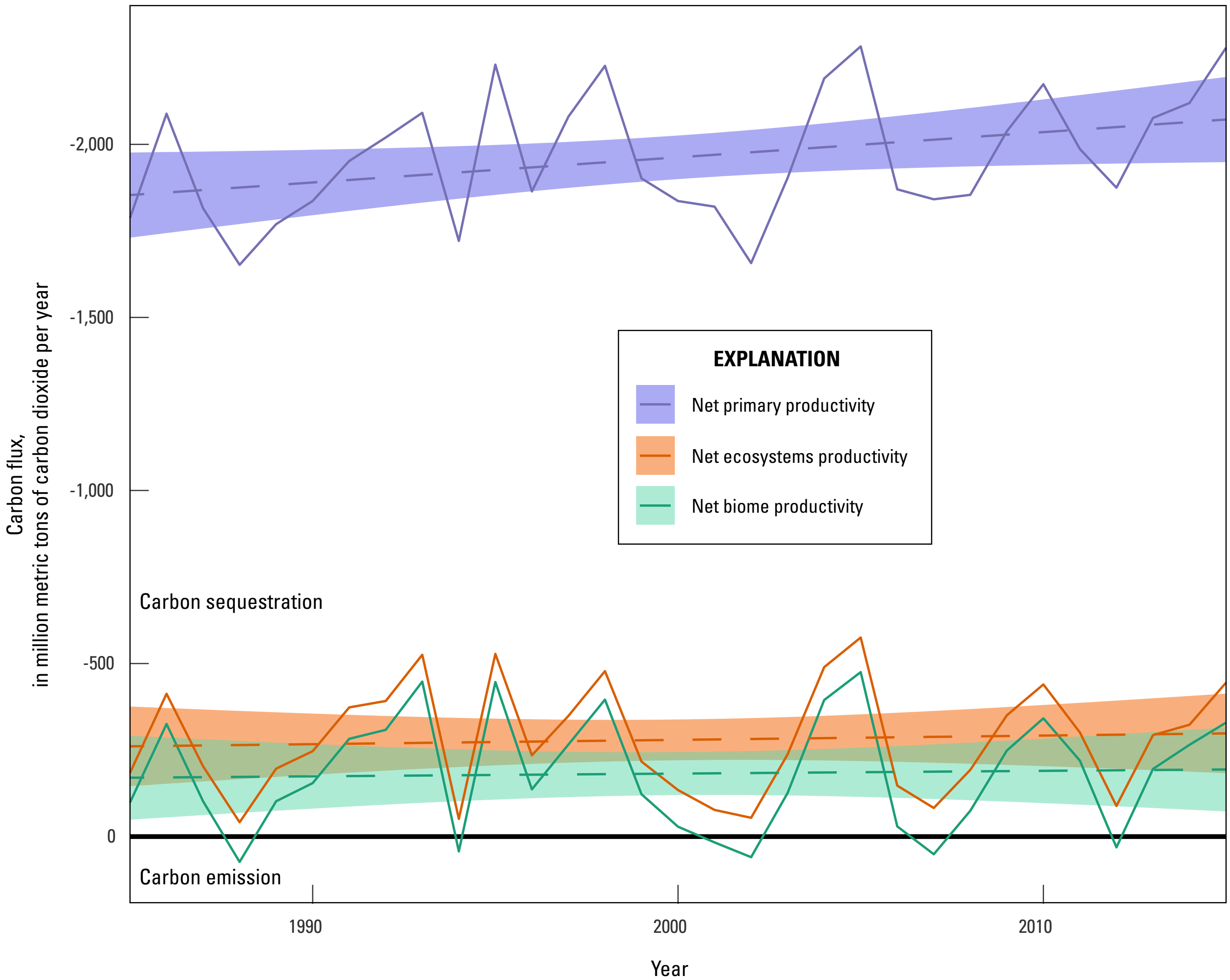


Figure 4. Graph showing estimates of annual rates of net primary productivity, net ecosystems productivity, and net biome productivity for the conterminous United States, 1985–2015. Negative values denote a net carbon sink or sequestration, and positive values denote a net carbon source to the atmosphere or emissions. Solid lines represent actual values, dashed lines are linear regression trend lines, and color bands indicate the standard error from those trend lines.

total carbon storage on Federal lands in the CONUS and accounted for 7.7 percent of the Federal land area. Conversely, Nevada accounted for the largest proportion of CONUS Federal land area (13.7 percent) but stored only 5.9 percent of the total carbon (4,882 MMT CO_2 Eq.). Of the 20 States with the largest Federal land area, the largest carbon storage densities were in North Carolina (1,736 metric tons of carbon dioxide equivalent per hectare [t CO_2 Eq./ha]), Florida (1,438 t CO_2 Eq./ha), and Michigan (1,416 t CO_2 Eq./ha), owing primarily to the formation of deep, organically rich peat soils.

Aside from Alaska (552 MMT CO_2 Eq./yr), California had the highest rate of NPP, averaging 256 MMT CO_2 Eq./yr. Nevada, which has the largest Federal land area in the CONUS, averaged 109 MMT CO_2 Eq./yr in NPP. The difference in mean annual carbon uptake can be attributed primarily to the proportion of forest lands found in California compared with Nevada. Forests remove carbon from the atmosphere at a much higher rate than regions dominated by grasslands and shrublands. Of the States with more than 5 million hectares of Federal land area, Washington had the highest rate of carbon uptake, averaging 19 metric tons of carbon dioxide equivalent per hectare per year (t CO_2 Eq./ha/yr). The highest uptake rate overall was found in Alabama, which averaged 32 t CO_2 Eq./ha/yr.

When ecosystem respiration, LULC, and disturbances were considered, Oregon was the largest net sink (highest NBP) of carbon on Federal lands at a rate of 30 MMT CO_2 Eq./yr.

Montana sequestered 19 MMT CO_2 Eq./yr. Alaska and Washington each sequestered 18 MMT CO_2 Eq./yr, followed by California (15 MMT CO_2 Eq./yr), Idaho (14 MMT CO_2 Eq./yr), Colorado (14 MMT CO_2 Eq./yr), and Wyoming (10 MMT CO_2 Eq./yr). Alaska had the largest mean annual carbon emissions from wildfire at 46 MMT CO_2 Eq./yr, followed by California and Idaho, which averaged 5 and 4 MMT CO_2 Eq./yr, respectively. Montana, Oregon, Florida, and Nevada all averaged 1 to 2 MMT CO_2 Eq./yr of fire emissions. The largest logging related carbon losses were found in Oregon and Washington, which averaged 7 and 4 MMT CO_2 Eq./yr, respectively.

Net Emissions and Sequestration Results

Combining the fossil fuel extraction and combustion emissions with the ecosystems emissions and sequestration estimates provides an informative summary result that includes both anthropogenic emissions and sequestration by ecosystems on Federal lands. This result is the net emissions value and is the sum of the total fossil fuel CO_2 emission value and the NBP, which is negative if carbon is stored and positive if carbon is emitted. The NBP reflects the absolute change in carbon stored within ecosystems on an annual basis. A positive net emission result indicates that emissions are greater than sequestration, whereas a negative value indicates that sequestration is greater than emissions. Ecosystems data were calculated for the period 1970–2015, but only the results for 2005–14 are provided in this report for comparison with fossil fuel-associated emissions estimates. In addition, sequestration data were not available for the Federal offshore areas, so net emissions values are not available for the offshore Pacific and offshore Gulf areas. The Hawaii sequestration values are not calculable on an annual level and are therefore excluded from the net emissions results. The net emissions results for 2005–14 are provided in table 6.

Annual net emissions data for the United States show variations that reflect the variation in the ecosystems NBP data. These variations are described in the terrestrial ecosystems-associated carbon emissions and sequestration "Results" section. In general, fossil fuel-associated emissions data show increasing or decreasing long-term trends but not significant annual variation. Whereas most major fossil fuel-producing States have positive net emissions, some States with lesser production alternate between positive and negative net emissions because ecosystem NBP (sequestration) values may be larger than the State's fossil fuel-associated emissions.

Table 6. Net emissions for Federal lands in the United States, 2005–14.

[All units are in million metric tons of carbon dioxide equivalent per year. Positive values indicate a net carbon emission, and negative values indicate a net carbon sequestration. Annual net biome productivity was not available for Hawaii and the offshore areas; therefore, U.S. total net emissions values are not included in this table. —, values were not calculated due to unavailability of annual terrestrial ecosystems-associated carbon emissions and sequestration]

State	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Alabama	0.2	2.9	5.6	0.9	−0.7	2.7	2.7	2.6	−2.6	−2.5
Alaska	–14.1	–14.6	–15.0	–14.9	–15.7	–16.1	–16.6	–16.8	–16.7	–16.5
Arizona	−28.8	23.9	24.3	−8.6	0	−15.6	14.8	14.4	−13.2	7.5
Arkansas	1.6	1.2	−0.9	−5	−4.2	0.9	−1.2	−0.9	−3	−5.3
California	−82.8	22.9	55.4	34.9	−22.8	−69	−24	35.2	13.4	28.6
Colorado	29.3	34.4	32.8	52.8	37.1	52.1	43.2	68.7	30.7	12.1
Connecticut	0	0	0	0	0	0	0	0	0	0.0
Delaware	−0.1	−0.1	0	0	0	0	−0.1	−0.1	−0.1	0.0
District of Columbia	−0.1	0	0	0	−0.1	0	0	0	0	−0.1
Florida	−1.6	5.4	5.4	−2.6	1.9	−3.2	3.1	−1.6	−1.8	−6.0
Georgia	−2.5	−1.2	2.7	−2.7	−5.9	−2.3	−0.4	−2.5	−4	−3.6
Hawaii	—	—	—	—	—	—	—	—	—	—
Idaho	−44.2	−7.7	7.1	0	−33.3	−38.3	−14.3	13.3	−1.3	−21.2
Illinois	−0.1	−1.2	0.1	−1.7	−1.1	0.6	−2.5	0.5	−0.9	−0.8
Indiana	−0.3	−1.8	−0.3	−2	−1.1	0.4	−2.2	−0.9	−1.3	−1.4
Iowa	−0.1	−0.1	−0.1	−0.1	−0.1	−0.1	−0.1	0	0	−0.1
Kansas	0.4	0.9	0.4	0.3	0.2	0.5	0.8	0.5	0.2	0.4
Kentucky	−0.7	1	3.9	−0.7	−4.4	−0.5	−8	−5.4	−5.9	−4.3

Table 6. Net emissions for Federal lands in the United States, 2005–14.—Continued

[All units are in million metric tons of carbon dioxide equivalent per year. Positive values indicate a net carbon emission, and negative values indicate a net carbon sequestration. Annual net biome productivity was not available for Hawaii and the offshore areas; therefore, U.S. total net emissions values are not included in this table. —, values were not calculated due to unavailability of annual terrestrial ecosystems-associated carbon emissions and sequestration]

State	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Louisiana	115.4	108.7	112.2	84.4	87.5	83	73.5	63	59.8	53.4
Maine	−0.2	−0.3	−0.2	−0.1	−0.2	−0.2	−0.2	−0.2	−0.2	−0.2
Maryland	−0.1	−0.1	0	−0.1	−0.1	0	−0.1	−0.1	−0.1	−0.2
Massachusetts	0	−0.1	0	0	−0.1	0	0	−0.1	0	0.0
Michigan	2.7	−2.9	−1.4	−1.4	−6.5	−0.7	−8.2	−7.1	−5.3	−6.6
Minnesota	−1.9	−0.7	0.5	−2.5	−3	−2.5	−1.6	−2	−1	−3.1
Mississippi	−0.5	3.3	1.8	−1.8	−3.5	−0.5	−2.9	−4.1	−4.2	−3.5
Missouri	−0.9	−1.6	−1.2	−5	−4.6	−0.9	−2.8	−0.2	−4.5	−1.8
Montana	15.6	44.4	41	35.3	37.9	4.2	22.3	34.1	23.7	20.2
Nebraska	−0.5	0.7	0.1	−0.7	−1.1	−0.9	−0.9	1.3	0.5	−1.2
Nevada	−61.3	17.8	43.7	20.6	−18.3	−16.7	0.8	26.8	−1.9	−14.7
New Hampshire	−0.6	−1.2	−2.2	−0.4	−1	−1.2	−1.1	−1.2	−1.2	−1.1
New Jersey	−0.1	−0.2	−0.2	−0.1	−0.2	0	−0.2	−0.4	−0.4	−0.2
New Mexico	68	66.6	67.6	63.3	71	58.7	72.5	79.7	63.5	68.6
New York	−0.1	−0.3	−0.1	−0.2	−0.3	−0.1	−0.3	−0.3	−0.3	−0.3
North Carolina	−3.3	−7	−4.9	−4.6	−7.9	−3.1	−5	−6.4	0.4	−3.6
North Dakota	2.5	7.7	9.2	8.3	2.7	0.2	7	14.5	12	12.4
Offshore Gulf	—	—	—	—	—	—	—	—	—	—
Offshore Pacific	—	—	—	—	—	—	—	—	—	—
Ohio	0.2	−0.9	0.5	−1.1	−1	0.1	−2.5	−1.5	−1.2	−0.6
Oklahoma	1.9	2.4	1	1	0.9	2	2.7	1.4	0.9	0.8
Oregon	−57.7	−13.4	−23	−8.4	−20.7	−48	−38.2	−22.7	−31.5	−32.8
Pennsylvania	−0.3	−0.8	−1.4	−1.1	−0.9	−0.2	−2.3	−2.2	−1.3	−1.5
Rhode Island	−0.1	0	0	0	−0.1	−0.1	0	0	0	−0.1
South Carolina	−1.3	−0.7	1.8	−0.1	−2	−0.6	−1	−0.8	−4.5	−2.0
South Dakota	−0.5	2.2	1.4	−6.1	−3.7	−7.3	−3.5	6	−3	−9.8
Tennessee	−2.1	−1.3	1.4	−0.6	−4.6	−1.9	−4.6	−4	−2.7	−2.4
Texas	29.5	28.3	21.1	17.9	17.8	13.6	16	9.7	6.6	3.2
Utah	4.8	37.1	50.7	55	31.6	28.5	14.4	55.3	38.8	25.2
Vermont	−0.1	−0.4	−1.3	−0.1	−0.8	−1.2	−0.1	−1.7	−1.5	−1.5
Virginia	−2.2	−0.6	−1.9	−0.9	−4.3	−3.1	−10.4	−7	−6.3	−5.1
Washington	−30.1	−8.9	−15.4	−15.1	−13.2	−27.7	−16.2	−14.5	−24	−16.7
West Virginia	−0.3	−2	−1.3	−4.1	−2.5	−0.4	−5.7	−4.7	−2.3	−1.9
Wisconsin	0.4	−0.7	0.8	−1.5	−1.5	−0.4	−2.2	−2.1	−1.8	−2.2
Wyoming	736	789.6	818.2	871	814.9	836.3	824.2	783.3	708.2	701.5

Conclusions

The USGS has produced estimates of fossil fuel-associated greenhouse gas emissions and terrestrial ecosystem-associated carbon emissions and sequestration for the Federal lands of the United States for 2005–14. Emissions associated with fossil fuel extraction and end-use combustion parallel production levels. States with significant fossil fuel production from Federal lands generally have higher estimated greenhouse gas emissions. Some States are significant producers of fossil fuels from non-Federal lands (such as State and private lands), and presumably have high emissions as well, but if the production is not from Federal lands, those emissions are not estimated here. Estimates of ecosystem carbon sequestration on Federal lands show that the amounts are highly variable owing to climate and weather, wildfires, land use and land-use changes, and other factors. States with the largest forests or Federal land holdings do not necessarily have the most significant ecosystem sequestration because soils retain more carbon than living matter does and ecosystems release carbon as well as store it. These factors highlight the complexity of the ecosystem sequestration calculation that is accounted for in the estimated results. The combined or net emission values included in this report are an informative, though simplistic, way of combining the two estimates.

These results are not intended or appropriate for ranking or comparing the States for many reasons. Firstly, the proportion of Federal lands to total lands varies considerably across each State. Secondly, these estimates report fossil fuel-associated emissions by the State of origin rather than the State where the emissions occurred. The data required to track all fossil fuels to their location of eventual end-use combustion are not available because of the structure of the United States' energy and industrial infrastructure. Thirdly, this study addresses the Federal lands-based scope that was given to the USGS; it was not designed to produce results for comparing States.

These USGS estimates provide a first-of-its-kind accounting for the emissions associated with fossil fuel extraction on Federal lands, the end-use combustion of those fuels, and the ecosystems sequestration and emissions of carbon on Federal lands. This information may provide context for future energy decisions, as well as serve as a reference to compare future changes in greenhouse gas emissions and carbon sequestration on Federal lands.

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Glossary

[See also table 3, "Explanation of carbon stock and flux terms from the terrestrial ecosystem sequestration calculations"]

abandoned coal mine emissions Emissions of methane, such as from offgassing or desorption, occurring after the cessation of extraction activities at a surface or underground coal mine.

active coal mine emissions Emissions of methane from ongoing extraction activities at a surface or underground coal mine.

combustion The process of burning fossil fuels to release energy.

emission factor A value that describes the greenhouse gas content of a fuel used in a particular sector of the economy or that indicates the amount of greenhouse gas emitted by a particular extraction activity.

estimated emissions Calculated estimates of greenhouse gases released by activities in various sectors of the economy.

estimated uptake Calculated estimates of carbon (represented in equivalent amounts of carbon dioxide, a greenhouse gas) sequestered or stored in plants and other organisms.

exported fuels emissions Emissions of greenhouse gases from coal, natural gas, and liquid petroleum products exported to other countries.

Federal lands Lands that are administered by various agencies of the U.S. Federal Government.

Federal offshore Areas seaward of State waters boundaries that are under the administration of the Bureau of Ocean Energy Management. Examples include the offshore Pacific area and offshore Gulf area.

fossil fuel A natural hydrocarbon material that is extracted and then combusted to release energy. Examples include coal, natural gas, crude oil, and various liquid petroleum products.

greenhouse gas Gases that cause the amount of solar thermal energy retained by the Earth's atmosphere to increase when their concentrations increase. The greenhouse gases discussed in this report are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).

mine abandonment The process by which an underground coal mine is closed. Examples include sealing, venting, and flooding. The abandonment process determines the emission factor used to calculate the amount of methane gas released from the abandoned mine over time.

mobile combustion emissions Emissions of greenhouse gases from fossil fuel combustion in the transportation sector.

petroleum and natural gas systems emissions Emissions of greenhouse gases from ongoing extraction activities and product transportation in the petroleum and natural gas industries.

stationary combustion emissions Emissions of greenhouse gases produced during the combustion of fossil fuels in all nontransportation sectors, including electricity generation, industrial feedstocks, and residential and commercial heating.

Appendixes 1–2

Appendix 1. Detailed Methods: Fossil Fuel-Associated Emissions of Greenhouse Gases from Federal Lands

Introduction

The methods described in this appendix are either very similar to those described in, or use outputs from, the U.S. Environmental Protection Agency (EPA) Inventory of U.S. Greenhouse Gas Emissions and Sinks (hereafter EPA Inventory; U.S. Environmental Protection Agency, 2016b). The methods were modified to suit the goals of this U.S. Geological Survey (USGS) study. Therefore, the EPA Inventory and associated annexes (U.S. Environmental Protection Agency, 2016a, b) are the best sources for the general methods described here. This description highlights general steps, sources for inputs, and areas where the USGS method differs from that of the EPA Inventory. Tables 1–1 through 1–6 include summary information on the sources for all input data used.

Stationary Combustion Emissions

Estimates of stationary combustion emissions for coal were calculated by using total State production volumes obtained from the Office of Natural Resources Revenue (ONRR) of the U.S. Department of the Interior via Memorandum of Agreement MOA16–5285. The production volumes were reduced to account for the coal that was exported in each year. The amount of coal produced on Federal lands and then exported was estimated by using the ratio of total State coal (private, State, and Federal combined) exported internationally to total State coal produced (U.S. Energy Information Administration, 2016a). Once the exports were subtracted from State production, the resulting amount was apportioned to the various sectors where coal is used domestically. For all coal sectors (electricity generation, commercial, industrial, and coking coal production), a basic process was followed. The State production minus exports was multiplied by State-level sector proportions that determined the "sector coal," or how much of the total coal was used in each sector (U.S. Energy Information Administration, 2016a). In the final step, the sector coal amounts were multiplied by carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emission factors to estimate the amounts of gases emitted. The emission factors used are specific to each sector and were reported by the EPA (U.S. Environmental Protection Agency, 2014) and references therein.

The method used to estimate emissions for natural gas follows the same general method described above for coal. The ONRR production data were the starting point. Data on dry gas production and exports are from the U.S. Energy Information Administration (EIA) (U.S. Energy Information Administration, 2016b). Sector proportions for industrial nonfuel use are from the EIA Manufacturing Energy Consumption Survey (U.S. Energy Information Administration, 2013), which is released every 5 years. All remaining natural gas was apportioned to a stationary combustion fuel-use sector. The EPA provided one set of emission factors for the stationary combustion of natural gas (U.S. Environmental Protection Agency, 2014). The amount of industrial nonfuel natural gas was reduced by a storage factor to account for the proportion of the natural gas that served as feedstock rather than being combusted (U.S. Environmental Protection Agency, 2016a).

Estimation of emissions from the combustion of various petroleum products started with crude oil production data provided by the ONRR. The crude oil volumes were converted to total State production volumes of refined products using national-level refining data (U.S. Energy Information Administration, 2015b). State-level refining information is not available for liquid fuels owing to the comingled nature of liquid fuel transportation in pipelines. Exports were subtracted from the total volumes (U.S. Energy Information Administration, 2015a), and the resulting volumes were apportioned to end-use sectors by using sector proportion data obtained from the EIA Monthly Energy Review (U.S. Energy Information Administration, 2016b). Lastly, the sector-specific petroleum product volumes were multiplied by the CO_2, CH_4, and N_2O emission factors for each sector from the EPA (U.S. Environmental Protection Agency, 2014). See table 1–1 for the inputs and sources mentioned in this section.

Mobile Sector Combustion Emissions

Estimates of emissions associated with combustion from mobile (transportation) uses were generated from ratios of emissions to fuel volumes combusted as reported by the EPA Inventory (U.S. Environmental Protection Agency, 2016b). Crude oil production volumes from the Federal lands in each State were obtained from the ONRR. The crude oil data were partitioned into estimated petroleum products (for example, gasoline, diesel oil, jet fuel, lubricants) on the basis of national refining products data (U.S. Energy Information Administration, 2015b). Export amounts were obtained from the EIA Petroleum Supply Annual (U.S. Energy Information Administration, 2015a). It was assumed that the national export ratios are the same as the export ratios for petroleum produced from Federal lands. Sector use information for each fuel was used to determine the proportions that were consumed in mobile uses (U.S. Energy Information Administration, 2016b).

The ratios of the U.S. annual emissions of CO_2, CH_4, and N_2O (U.S. Environmental Protection Agency, 2016b) to the annual mobile fuel consumption (U.S. Environmental Protection Agency, 2016a) provided values of emissions per gallon of fuel consumed (by gas and type of fuel). These values were multiplied by the volumes of fuels sourced from Federal lands and consumed domestically to estimate the emissions for each

fuel. This method reasonably assumes that the national emissions ratios are representative of the emissions ratios expected for fuels from Federal lands. See table 1–2 for the inputs and sources mentioned in this section.

Petroleum and Natural Gas Systems Emissions

Total national emissions from petroleum and natural gas systems (CO_2 and CH_4 emitted from production through distribution) (U.S. Environmental Protection Agency, 2016b) were divided by the national oil and natural gas well counts (U.S. Environmental Protection Agency, 2017a, b), resulting in ratios of CO_2 and CH_4 emissions per well for petroleum and natural gas systems. These national ratios were then multiplied by the numbers of Federal producing oil and gas wells in a State to estimate emissions. For the years included in this study (2005–14), State-level Federal lands well counts were available for 2014 only (Bureau of Land Management, written commun., 2016). To generate Federal lands well counts for other years, the 2014 State Federal lands wells were divided by the total State wells, to produce a State-specific Federal lands to total well ratio. This ratio was then used to approximate State Federal lands wells counts from available annual State well totals.

A time series of producing natural gas wells by State for 2005–14 was available from the U.S. Energy Information Administration (2016c). A similar time series of oil wells by State was not available for the study period, so various sources were compiled. Oil well counts for 2005–8 were from the U.S. Energy Information Administration (2009). Oil well counts for 2009–10 and 2013–14 came from World Oil (World Oil, 2011, 2014; Abraham, 2015; Jordan, 2016). State data were not readily available for 2011 and 2012, so trendlines fit to the data were used to estimate missing values. However, as of the time of publication of this study, State oil well data are now available through the EIA's "U.S. Oil and Natural Gas Wells by Production Rate" report (U.S. Energy Information Administration, 2017).

Table 1–1. Inputs and sources for the stationary combustion greenhouse gas emissions estimate.

Input	Source
Coal, crude oil, and natural gas production volumes from Federal lands	Office of Natural Resources Revenue, data obtained via Memorandum of Agreement MOA16–5285
Coal: export data	U.S. Energy Information Administration, 2016a
Coal: sector use proportions	U.S. Energy Information Administration, 2016a
Coal: sector-specific emission factors	U.S. Environmental Protection Agency, 2014
Natural gas: export data	U.S. Energy Information Administration, 2016b, table 4.1
Natural gas: sector use proportions	U.S. Energy Information Administration, 2013
Natural gas: emission factors	U.S. Environmental Protection Agency, 2014
Natural gas: nonenergy storage factor	U.S. Environmental Protection Agency, 2016a, table A–62
Petroleum products: refining data	U.S. Energy Information Administration, 2015b
Petroleum products: export data	U.S. Energy Information Administration, 2015a
Petroleum products: sector use proportions	U.S. Energy Information Administration, 2016b, tables 3.5 and 3.7
Petroleum products: sector-specific emission factors	U.S. Environmental Protection Agency, 2014

Table 1–2. Inputs and sources for the mobile sector combustion greenhouse gas emissions estimate.

Input	Source
Crude oil production volumes from Federal lands	Office of Natural Resources Revenue, data obtained via Memorandum of Agreement MOA16–5285
Petroleum products: refining data	U.S. Energy Information Administration, 2015b
Petroleum products: export data	U.S. Energy Information Administration, 2015a
Petroleum products: sector use proportions	U.S. Energy Information Administration, 2016b, tables 3.5 and 3.7
Annual mobile fuel consumption	U.S. Environmental Protection Agency, 2016a, table A–92
Annual carbon dioxide mobile emissions	U.S. Environmental Protection Agency, 2016b, table 3–12
Annual methane mobile emissions	U.S. Environmental Protection Agency, 2016b, table 3–13
Annual nitrous oxide mobile emissions	U.S. Environmental Protection Agency, 2016b, table 3–14

To quantify the variation between the data used for this study and the newly available and complete time series data from the EIA, consider the comparison of Wyoming well counts from both datasets. Oil well counts from this study and the new data are nearly identical for the period 2005–8. Variation from 2010 to 2014 was evident: the study dataset oil well counts are on average 14 percent lower than the EIA dataset. Conversely, gas well counts from this study and the new data are nearly identical from 2010 to 2014. Study dataset gas well counts are on average 15 percent lower than the new dataset from 2005 to 2008. These variations are due to differing gas-oil ratios used to define well type, methods of accepting data from States, and State reporting schedules.

To review, all well counts in the new EIA dataset are higher or unchanged compared to those used in this study. If the new dataset had been available during the analysis phase, its use would have resulted in a lower ratio of State Federal lands wells to total State wells, therefore reducing the onshore emissions for petroleum and natural gas systems attributed to activities on Federal lands. Using this new dataset would be a methodological improvement; however, in terms of significance, note that the EPA's uncertainty on the emissions estimate is −25 to 45 percent and that the methods for estimating emissions are an area of rapidly evolving science.

Total offshore oil and gas platform counts were obtained from the EPA (U.S. Environmental Protection Agency, 2017a, b). The total platform counts were split into offshore Pacific and offshore Gulf counts by subtracting the estimated number of Pacific platforms (a relatively small number) from the EPA's totals. The 2011 Pacific drilling platform counts are from Bureau of Ocean Energy Management (Bureau of Ocean Energy Management, 2011) available on the National Oceanic and Atmospheric Administration-hosted Marine Cadastre website. These platform counts were used for all years in the estimate (2005–14) because historical data were not available. The depths and types (oil versus gas) of the offshore Pacific platforms were determined by using National Oceanic and Atmospheric Administration spatial bathymetry data (National Oceanic and Atmospheric Administration, 2013) and proprietary USGS oil and gas databases.

This report follows guidance from the EPA (U.S. Environmental Protection Agency, 2015) on emission factors for offshore platforms. Those factors originate from the Gulf Offshore Activity Data System and are based on emissions reported for 2011 (Wilson and others, 2014). For further information on the choice of emission factors, consult the EPA guidance (U.S. Environmental Protection Agency, 2015). Estimates of emissions from offshore platforms vary over the years included in this estimate (2005–14) because reporting initiatives, emissions research, and on-site improvements continue to develop. Newer estimates of emissions from offshore production are available from the Gulf Offshore Activity Data System (Wilson and others, 2017). The emission factors used here are specific to both the water depth—deep, depths greater than 656 feet (200 meters); shallow, depths less than 656 feet (200 meters)—and the main hydrocarbon produced (oil or gas). The number of platforms in each depth and product category was multiplied by the emission factors to generate the estimate. See table 1–3 for the inputs and sources mentioned in this section.

Active Coal Mine Emissions

Emissions of CH_4 from active underground coal mines were calculated as the sum of four kinds of emissions: ventilation, degasification, recovered/used, and postmining. Emissions of CH_4 from ventilation and degasification, as well as amounts of CH_4 recovered, are measured directly by the Mine Safety and Health Administration or reported by mine operators (the larger value was used when both measures were available). For underground mines, postmining CH_4 emissions are the product of annual production, the basin-specific in situ coal CH_4 content, and a fixed postmining emission factor of 0.325 (U.S. Environmental Protection Agency, 2016a).

Active surface mine emissions of CH_4 are the product of annual production, basin-specific in situ coal CH_4 content, and a fixed surface mining emission factor of 1.5 (U.S. Environmental Protection Agency, 2016a). The method for estimating postmining emissions for active surface mines is the same as that described above for post-mining emissions for active underground mines. See table 1–4 for the inputs and sources mentioned in this section.

Abandoned Coal Mine Emissions

The CH_4 emissions from abandoned underground coal mines were calculated with an emissions decline curve that used the active emissions on the day of abandonment as the starting point. The variables that control the type of decline curve are specific to the method of abandonment (sealing, venting, or flooding). Emissions from mines with an unknown abandonment method were determined by calculating the emissions for all three methods of abandonment and then using a weighted average of the outputs based on region-specific abandonment-method statistics. The EPA's methodology (Franklin and others, 2004; U.S. Environmental Protection Agency, 2004) for abandoned mines was the general method applied. However, unlike the EPA's probabilistic approach, this USGS estimate is deterministic and was obtained by using single region-specific median inputs in the decline curve calculations rather than a range of potential values. This simplification does not significantly affect the results and is in line with the simplified approach used in the USGS estimate. See table 1–5 for the inputs and sources mentioned in this section.

Exported Fuels Emissions

Emissions associated with exported fuels were estimated using the same methods as the domestic stationary and mobile combustion calculations. See those sections of this appendix for details. The portion of the fuel produced from Federal lands that was used in this calculation was based on export information from the EIA (table 1–6).

Table 1–3. Inputs and sources for the petroleum and natural gas systems greenhouse gas emissions estimate.

[CO_2, carbon dioxide; CH_4, methane]

Input	Source
CO_2 and CH_4 natural gas systems emissions	U.S. Environmental Protection Agency, 2016b, tables 3–46 and 3–49
CO_2 and CH_4 petroleum systems emissions	U.S. Environmental Protection Agency, 2016b, tables 3–38 and 3–36
National Producing oil and gas well counts	U.S. Environmental Protection Agency, 2017a, b
State Producing oil well counts	U.S. Energy Information Administration, 2009; World Oil, 2011, 2014; Abraham, 2015; Jordan, 2016
State Producing gas well counts	U.S. Energy Information Administration, 2016c, table 5
State Federal lands producing oil and gas well counts	Bureau of Land Management, written commun., 2016
Offshore platform emission factors	U.S. Environmental Protection Agency, 2015, table 1
Total offshore platform counts	U.S. Environmental Protection Agency, 2017a, b
Pacific offshore platform counts	Bureau of Ocean Energy Management, 2011

Table 1–4. Inputs and sources for the active coal mining greenhouse gas emissions estimate.

[CH_4, methane]

Input	Source
Production, fuel type, and basin information	Office of Natural Resources Revenue, data obtained via Memorandum of Agreement MOA16–5285
Basin-specific in situ coal CH_4 content	U.S. Environmental Protection Agency, 2016a, table A–123
Annual ventilation CH_4 volumes	U.S. Environmental Protection Agency, Inventory of U.S. Greenhouse Gas Emissions and Sinks project team, written commun., 2016 (data reported by the Mine Safety and Health Administration)
Annual degasification CH_4 volumes	U.S. Environmental Protection Agency, Inventory of U.S. Greenhouse Gas Emissions and Sinks project team, written commun., 2016 (data reported by the Mine Safety and Health Administration
Annual recovered/used CH_4 volumes	U.S. Environmental Protection Agency, Inventory of U.S. Greenhouse Gas Emissions and Sinks project team, written commun., 2016 (data reported by the Mine Safety and Health Administration)
Postmining emission factors	U.S. Environmental Protection Agency, 2016a, table A–123

Table 1–5. Inputs and sources for the abandoned coal mine greenhouse gas emissions estimate.

Input	Source
Abandoned Federal lease mines	U.S. Environmental Protection Agency, Inventory of U.S. Greenhouse Gas Emissions and Sinks project team, written commun., 2016; John Hovanec, Office of Natural Resources Revenue, written commun., 2016
Date of abandonment	U.S. Environmental Protection Agency, Inventory of U.S. Greenhouse Gas Emissions and Sinks project team, written commun., 2016 (data reported by the Mine Safety and Health Administration)
Average emissions at abandonment	U.S. Environmental Protection Agency, Inventory of U.S. Greenhouse Gas Emissions and Sinks project team, written commun., 2016 (data reported by the Mine Safety and Health Administration)
Abandonment method	U.S. Environmental Protection Agency, Inventory of U.S. Greenhouse Gas Emissions and Sinks project team, written commun., 2016 (data reported by the Mine Safety and Health Administration)
Decline curve values	Franklin and others 2004; U.S. Environmental Protection Agency, 2004
Abandonment method by basin	Franklin and others, 2004; U.S. Environmental Protection Agency, 2004

Table 1–6. Inputs and sources for the exported fuels greenhouse gas emissions estimate.

Input	Source
Coal export data	U.S. Energy Information Administration, 2016a
Natural gas export data	U.S. Energy Information Administration, 2016b
Petroleum products export data	U.S. Energy Information Administration, 2015a

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Appendix 2. Detailed Methods: Terrestrial Ecosystems-Associated Carbon Emissions and Sequestration on Federal Lands

Introduction

For this U.S. Geological Survey study, we used a dynamic global vegetation model to estimate net primary productivity (NPP), net ecosystem productivity, and net biome productivity for all Federal land areas in the conterminous United States. Within these areas, we estimated the changes in carbon stocks and fluxes for forests, grasslands, shrublands, wetlands, and agricultural lands resulting from processes associated with deforestation, afforestation, reforestation, agricultural contraction and expansion, urbanization, forest harvest, and wildfire. Historical changes in land use and land cover (LULC) were estimated from a range of remote sensing-based datasets. Carbon dynamics within the dynamic global vegetation model were calibrated on the basis of forest and agricultural inventory data from the U.S. Department of Agriculture (USDA) and remote sensing estimates of NPP.

Integrated Biosphere Simulator Dynamic Global Vegetation Model

For this study, the following LULC changes were considered: logging, deforestation (forest to agriculture conversion), afforestation (agriculture to forest conversion), agriculture contraction (agriculture to grassland conversion), agriculture expansion (grassland to agriculture conversion), and urbanization (forest to urban, grassland to urban, and agriculture to urban conversion). The Integrated Biosphere Simulator (IBIS) models fractional vegetation cover within a single land pixel, which enables the model to run at coarse resolution (1 kilometer [km]) derived from high-resolution LULC products (for example, 30 meters [m]) (Liu and Sleeter, 2018). Most of the land pixels are a mixture of several land-cover types. The IBIS model tracks the percent area of each land-cover type within each land pixel. When an LULC or disturbance event (for example, reforestation, deforestation, or urbanization) occurs, cover fractions are transferred between the relevant land-cover types.

In addition to disturbances detectable through remote sensing methods, less detectable events like forest thinning activities were also considered. The forest thinning rate was calculated using recent annualized forest inventory data (Zhou and others, 2013). Thinning activity was loosely defined as the cutting-related vegetation carbon loss of less than 50 percent during two consecutive observation periods (around 5 years) in order to make the overall thinned-area percentage (that is, 61 percent of the total forest cutting area) in agreement with earlier estimates (Masek and others, 2011; Oswalt and Smith, 2014).

Model calibrations were performed by comparing ecoregion-level NPP, live vegetation, dead vegetation, and crop yield with observations. Observations included remote sensing-derived, 1-km-resolution Moderate Resolution Imaging Spectrometer NPP products for 2001–5 (Zhao and others, 2005), Forest Inventory and Analysis program-derived forest live and dead vegetation growth curves obtained from the Carbon OnLine Estimator (Van Deusen and Heath, 2015), and county-level agricultural data (U.S. Department of Agriculture, 2011). During calibration, NPP and grain-yield scalars were generated on the basis of differences between IBIS outputs and observations. The scalars were then used to modify the maximum Rubisco-limited rate of carboxylation (Vmax) of related plant functional types (forest or crop) in a new IBIS run. For the forest live and dead vegetation calibration, 100 years of growth of live and dead vegetation from IBIS simulation were compared with the Carbon OnLine Estimator data. Scalars were generated to modify the tree mortality rate and the transfer rate of deadwood to ground litter.

Data Sources

Input data related to land cover include (1) 30-m vegetation-cover type and vegetation-height information from the USDA–U.S. Department of the Interior LANDFIRE program (Rollins, 2008), (2) five dates of 60-m resolution land-cover-type information from the U.S. Geological Survey (USGS) Land Cover Trends project (Loveland and others, 2002; Sleeter and others, 2013), (3) 30-m resolution annual wildland fire scar and burn severity information from the USGS–USDA Monitoring Trends in Burn Severity project (Eidenshink and others, 2007), and (4) freshwater and saline water wetland-fraction map derived from 30-m USGS National Land Cover Database and National Oceanic and Atmospheric Administration Coastal Change Analysis Program data (Homer and others, 2007). All land-cover maps were aggregated to a consistent 960-m resolution in this study. In addition, regional rates of forest stand thinning were derived from previous studies (Law and others, 2012; Zhou and others, 2013). We used Parameter-elevation Regression on Independent Slopes Model 4-km resolution monthly precipitation and temperature data from 1971 to 2010 as the main climate drivers (Daly and others, 2008). Other climate variables, such as relative humidity and wind speed, were monthly normals for 1961–90. The Soil Survey Geographic Database (Natural Resources Conservation Service, 2009) soil carbon content was used to initialize soil condition. For the period 2011–15, no changes in LULC were modeled owing to a lack of spatially explicit data. However, fire and climate data were available and were used in the model simulations.

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